Human Perception and Indication of the Vertical: Experiments and Models

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General rules:

1. α represents a physical angle, which is a vector. It is physically measurable. For example, the angle between the head and the torso has both direction and magnitude.

2. S represents a physiological signal such as nerve firing rate, which is also measurable in animals.

3. β represents a psychological quantity or perception which is a scalar. It is not measurable but can sometimes be reported or indicated.

4. W weighting coefficient.

5. In case of α and β, a subscript indicates what a symbol represents; a superscript indicates the reference, or what the measurement is made against. For example, α_H^T means the tilt of the *H*ead in the *T*orso coordinates, or relative to the *T*orso. In the case of S and W, a sub- and superscript indicates the contributing sensory organ, and the contributed perception. For example, S_o^t represents the portion of physiological signals from the *o*tolith organs contributing to the perception of the torso tilt.

6. Vectors such as α always have capital sub- and superscripts since the sub- and superscripts correspond to physical positions. Scalars such as S and β always have lowercase sub- and superscripts since the sub- and superscripts do not correspond to any physical position here. For example, α_H^T represents the tilt of the *H*ead relative to the *T*orso; whereas β_h^t represents the perception of the tilt of the *h*ead relative to the subjective *t*orso.Here neither the head nor the subjective torso position has a definite position at the perceptual level. In other words, only the relative quantity is meaningful.

α_T^{GV} Physical tilt of the *T*orso measured from the *G*ravitational *V*ertical.

α_H^T Physical tilt of the *H*ead in *t*orso coordinates, measured from the *T*orso.

α_H^{GV} Physical tilt of the *H*ead, measured from the *G*ravitational *V*ertical.

α_{VL}^{GV} Physical tilt of the *V*isual *L*ine, measured from the *G*ravitational *V*ertical.

α_{VL}^E Physical tilt of the *V*isual *L*ine in *E*ye coordinates, measured from the vertical meridians of the eyes.

α_E^H Physical tilts of the *E*yeballs in *H*ead coordinates, i.e. the ocular counterrotation.

α_{VL}^H Physical tilt of the *V*isual *L*ine in *H*ead coordinates or measured from the median line of the head.

α_R^{GV} Physical tilt of the *R*od measured from the *G*ravitational *V*ertical.

α_R^T Physical tilt of the *R*od in *t*orso coordinates or measured from the median line of the torso.

β_{VSV}^{GV} *VSV* indication (error): the angle between the *V*isual indication of *S*ubjective *V*ertical and the *G*ravitational *V*ertical.

β_{VST}^{GV} *VST* indication (error): the angle between the *V*isual indication of *S*ubjective *T*orso position and the *G*ravitational *V*ertical.

α_{KSV}^{GV} *KSV* indication (error): the angle between the *K*inesthetic indication of *S*ubjective *V*ertical and the *G*ravitational *V*ertical.

β_{VKSIM}^{VL} *VKSIM* indication (error): the angle between a visual line display and its kinesthetic indication.

α_{HB} A kinesthetic indication bias in degree, caused by hand kinesthetic bias S_{hb}.

α_{NB} A kinesthetic indication bias in degree, caused by neck kinesthetic bias S_{hb}.

α_{TB} A kinesthetic indication bias in degree, caused by torso kinesthetic bias S_{hb}.

α_{KB} Total kinesthetic indication bias in degree, caused by the total kinesthetic bias S_{kb}.

S_t Physiological signals from the *t*orso sensors.

S_o Physiological signals from the *o*tolith organs.

S_n Physiological signals from the *n*eck sensors.

S_o^t The portion of physiological signals from the *o*tolith organs contributing to the perception of the torso tilt.

S_o^h The portion of physiological signals from the *o*tolith organs contributing to the perception of the head tilt.

W_t^t A weighting coeffecient, indicating the weight of the physiological signal S_t in the perception of the torso tilt.

W_o^t A weighting coeffecient, indicating the weight of the physiological signal S_o^t in the perception of the torso tilt.

W_n^h A weighting coeffecient, indicating the weight of the physiological signal S_n in the perception of the head tilt.

W_o^h A weighting coeffecient, indicating the weight of the physiological signal S_o^h in the perception of the head tilt.

W_t^o A weighting coeffecient, indicating the weight of the physiological signal S_t in the perception of the overall head tilt.

W_n^o A weighting coeffecient, indicating the weight of the physiological signal S_n in the perception of the overall head tilt.

W_o^o A weighting coeffecient, indicating the weight of the physiological signal S_o in the perception of the overall head tilt.

S_{hb} Hand kinesthetic bias in expressed physiological signals.

S_{nb} Neck kinesthetic bias in expressed physiological signals.

S_{tb} Torso kinesthetic bias in expressed physiological signals.

S_{kb} Total kinesthetic bias in expressed physiological signals.

S_r^t Physiological signals from operating hands' joint receptors, reflecting the angle between the *R*od, *R*P or P*R*P Indicator and the torso; including S_r^{gv} and S_t^{gv}.

$\hat{S}_r^t$ Biased or modulated physiological signal representing the angle between the *R*od, *R*P or P*R*P Indicator, and the torso; it is the sum of S_r^t and S_{kb}.

S_r^{gv} A part of S_r^t, caused by the initial rod position relative the the gravitational vertical.

S_t^{gv} A part of S_r^t, caused by the tilt of the torso from the the gravitational vertical.

β_t^{cv} Perceived tilt of the *t*orso relative to the *c*ontrol *v*ertical.

β_h^t Perceived tilt of the *h*ead relative to the perceived, or subjective, torso position.

β_h^{cv} Perceived tilt of the *h*ead, or perceived overall head tilt relative to the *c*ontrol *v*ertical.

β_{srf}^t Constructed position of the *srf* z-axis relative to the perceived, or subjective, torso position.

β_t^h Constructed position of the *t*orso relative to the perceived head position or the subjective *h*ead position.

β_{srf}^h Constructed *srf* position relative to the perceived, or subjective, head position.

β_{vl}^e Perceived tilt of the *v*isual *l*ine relative to the perceived position of the vertical meridians of the eyes.

β_{vl}^h Perceived tilt of the *v*isual *l*ine relative to the perceived, or subjective, head position.

β_{vl}^{srf} Perceived tilt of the *v*isual *l*ine in the *srf* coordinates.

β_r^{srf} Perceived tilt of the *r*od in the *srf* coordinates.

β_r^t Perceived tilt of the *r*od relative to the perceived *t*orso position or the subjective torso position.

β_{hb} Perceptual bias in degree caused by the hand kinesthetic bias signal S_{hb}.

β_{nb} Perceptual bias in degree caused by the neck kinesthetic bias signal S_{nb}.

β_{tb} Perceptual bias in degree caused by the torso kinesthetic bias signal S_{tb}.

β_{kb} Total percuptual bias in degree caused by the total kinesthetic bias signals S_{kb}.

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Abstract

A series of experiments investigating human perception of the vertical was carried out at the Man-Vehicle Laboratory at MIT. These experiments included a *Kinesthetic Subjective Vertical* (KSV), *Inclination Indication with Unseen Hand(s)* (IIUH) and three *Visual-Kinesthetic Spatial Inclination Matching* (VKSIM) experiments. The relationship between a subject's performances in the visual and kinesthetic modalities was examined.

In the KSV experiment, the subjects were told to align a rod to the vertical in the roll plane. Their heads were upright, tilted 90^o left or 90^o right, and their eyes were closed. When their heads were tilted, subjects showed a strong bias in their indications (range $8^o - 18^o$) in the direction opposite to the tilt of their heads ($P << 0.001$). This is opposite to the results in the classic *Visual Subjective Vertical indication (VSV)* experiments by Müller and others. The discrepancy was on the order of 15^o–20^o.

In the VKSIM experiments, the cause was thought to be three types of kinesthetic indication biases. The first, ***hand bias***, is caused by the use of a single hand for indication. The second, ***neck bias***, is associated with a tilt of the head relative to the torso. The third, ***torso bias***, is associated with a torso tilt relative to the upright posture. It was hypothesized that these biases were generated by asymmetrical neuro-muscular activities.

A heuristic model was established to postulate the mechanism of human perception and indication of the vertical. The model, using an unconventional concept of *Subjective Reference Frame*, successfully explains many seemingly contridictory results in the field of human perception and indication of the vertical.

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Chapter 1

Introduction

Human spatial orientation with respect to the gravitational vertical has been investigated for more than a century. In the late nineteenth and early twentieth centuries, intensive experimentation was devoted to research on the influence of body and/or head tilts on human perception and indication of the vertical. This exploration dates back to H. Aubert in 1861. One day when his head was tilted, he accidentally discovered that a vertical streak of light in an otherwise dark room appeared to be set inclined in the opposite direction [1]. Consequently, to make the streak of light appear upright, the light had to be tilted from the vertical towards the same side as the tilt of his head. This effect has been referred to as the "*Aubert-effect*" or "*A-effect*". Later, in 1916, Müller found the opposite effect with small tilts of the head, which was referred to as the "*Müller-effect*" or "*E-effect*" [24]. He further concluded that for most people, *E-effects* occur with small angles of head tilts and *A-effects* occurs with large ones [24]. Figure 1.1 illustrates the pattern of occurence of the *A*- and *E-effects* by using the approximated values of Bauermeister's data [2]. The two terminologies are further described in the following statements:

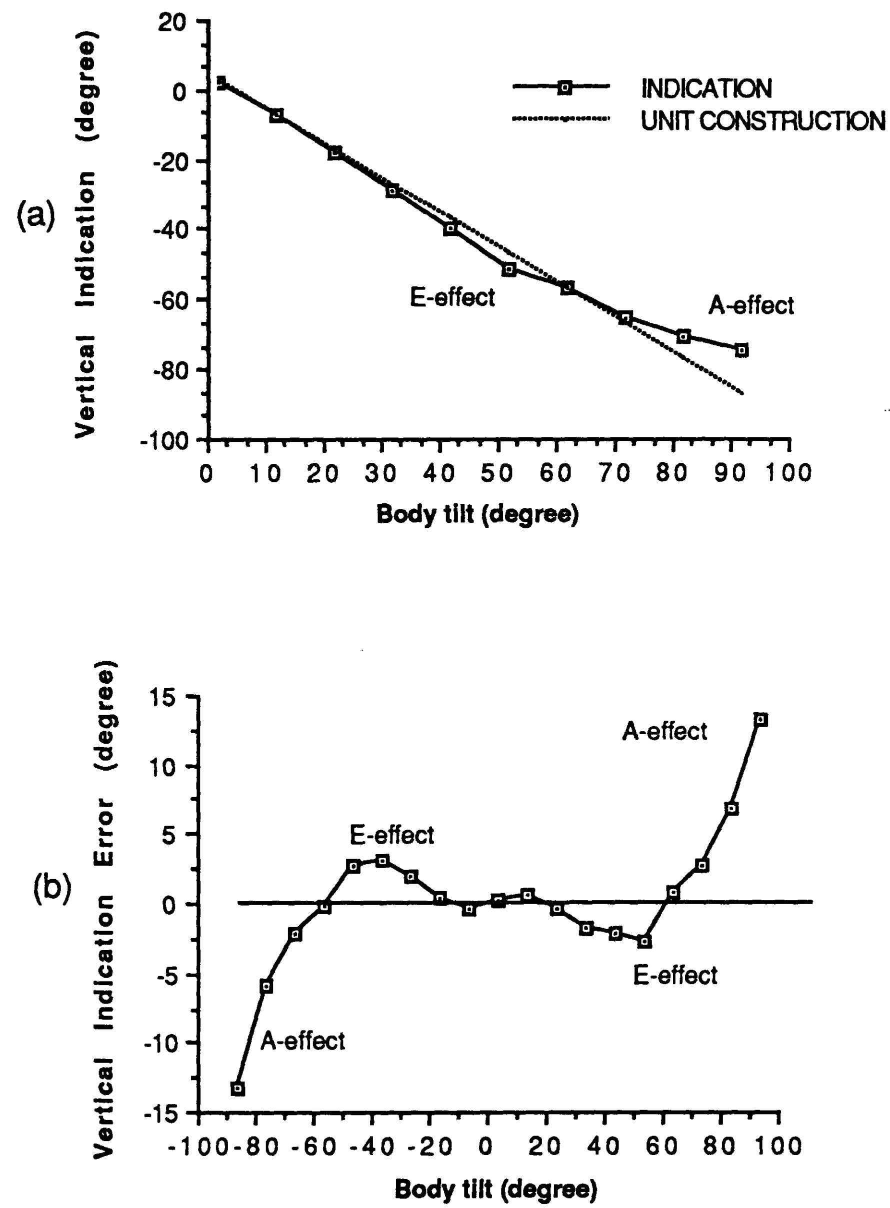


Figure 1.1: Illustration of the occurences of A- and E-effects

(using approximated values of Bauermeister's data)

An angle is positive if it is clockwise in a subject's own view, is negative if it is measured counterclockwise. (a) Indication of the vertical measured from the subject's body; (b) Indication error measured from the true vertical.

A-effect: When a subject tilts his head to one side, a vertical luminous line in an otherwise dark room is visually perceived by the subject as tilted, from the vertical, in the direction opposite to the tilt of the head. Consequently, when asked to align the luminous line to the vertical, the setting is inclined from the true vertical, in the same direction as the tilt of the head.

For example, when a subject views a vertical luminous line while his head is tilted to his right, he sees the vertical line as tilted to the left. If asked to align a luminous line indicator to the vertical, he will set the indicator tilted to the right. This was interpreted by Aubert and others as the consequence of under-estimation of the angle of the head tilt from the true vertical by the subject [1,59,13].

E-effect: When a subject tilts his head to one side, a vertical luminous line in an otherwise dark room is visually perceived by the subject as tilted, from the vertical, in the same direction as the tilt of his head. Consequently, when asked to align the luminous line to the vertical, the setting is inclined from the vertical in the direction opposite to the tilt of the head.

For instance, when a subject views a vertical luminous line with his head tilted to his right, he sees the vertical line as tilted to the right. If asked to align a luminous line indicator to the vertical, he will set the indicator tilted to the left. This was interpreted by some investigators as the consequence of over-estimation of the angle of the head tilt from the vertical by the subject [59].

The position of the indicator in the above statements is from now on referred to as the *indicated vertical*.

The *A*- and *E-effects* were originally introduced by Müller in Visual Subjective Vertical (referred to as VSV from now on) perception and indication studies in which a subject's head was tilted. Later researchers extended these two terminologies to describe the analogous effects in the Kinesthetic Subjective Vertical (referred to as KSV from now on) indication studies, with not only a subject's head, but also whole body tilted. For instance, a blindfolded subject with the head or whole body tilted right would use his hands to perceive a vertical rod as tilted either to the left (***kinesthetic A-effect***) [34] or to the right (***kinesthetic E-effect***) [3,4,26,35,56].

Since Visual Subjective Vertical perception and indication has been the center of human orientation research, people have accepted Müller's findings as a general model for prediction. Although some investigators obtained different results in the kinesthetic modality, they failed to investigate the discrepancy between their results and Müller's. Instead, they analyzed their results without consideration to Müller's findings. Consequently, people have gradually overlooked the differences between visual and kinesthetic indications of the vertical.

It is also widely accepted that the otolith organs are largely responsible for the occurrence of the A- and E-effects. Therefore, it would be very interesting to see how the unloading of that organ for a period of time affects the perception of the vertical. To answer this question, we planned to compare astronauts' vertical indications before and after a space flight. The initial aim of this project was to determine an appropriate test procedure for a space shuttle/spacelab experiment. In order to collect the data immediately after landing, postflight measurements must be made inside the cabinet of a space shuttle. A simple apparatus and method are therefore mandatory. A completely dark environment is very difficult to achieve inside the cabinet of a space shuttle, and a helmet with a luminous line display would be too big to store onboard. Therefore, a pocket *Rod & Pendulum Indicator* (*RP Indicator* in short) was made for this purpose. The idea was to ask the astronauts to hold the RP Indicator aligned with the vertical with their head upright, or tilted 90° to the side, both before and immediately after a space flight. Therefore, a prototype experiment of Kinesthetic Subjective Vertical Indication was conducted in our laboratory. Based on Müller's generalization, the A-effect was expected pre-flight measurement. But in the protocol experiment (Kinesthetic Subjective Vertical indication, or KSV), the subjects showed large E-effects in their indications. At that time, we failed to consider the difference between a perception and an indication of the vertical. We were also unaware of the differences between the visual and kinesthetic indications of the vertical. Therefore, we thought that these KSV results contradicted Müller's generalization, as well as another theory established in our laboratory [29,30]. To explore the underlying mechanism, a series of experiments has been conducted including *Inclination Indication with Unseen Hand(s) (IIUH)* and three *Visual Kinesthetic Spatial Inclination Matching (VKSIM)* experiments. The following chapters are devoted to presenting the results and a derived heuristic model.

Chapter 2

Experiments and Results

2.1 Kinesthetic Subjective Vertical Experiment (KSV)

2.1.1 Procedure

A seated subject with his eyes closed was asked to hold a ***Rod and Pendulum Indicator (RP Indicator)*** (see section 2.1.2 for description) to the vertical with his ***dominant hand***[1]. The tests were done at three different head positions: upright, tilted 90° to the left, or 90° to the right. The subject rested his head on a horizontal table at his side, with his left or right ear down, to achieve the 90° head tilts. The head tilts were visually verified by the experimenter. Notice that a pure head tilt cannot exceed about 45°, thus a 90° tilt of the head requires both the torso and the neck being tilted. The dial face of the *RP Indicator* was always kept in a vertical plane parallel to the subject's frontal plane (in short, vertical frontal-parallel plane) with visual monitoring by the experimenter (see figure 2.1). The test was occasionally interrupted by the experimenter to correct the subject by turning the

[1]Here a ***dominant hand*** means the hand a subject reported as more frequently used in the daily life.

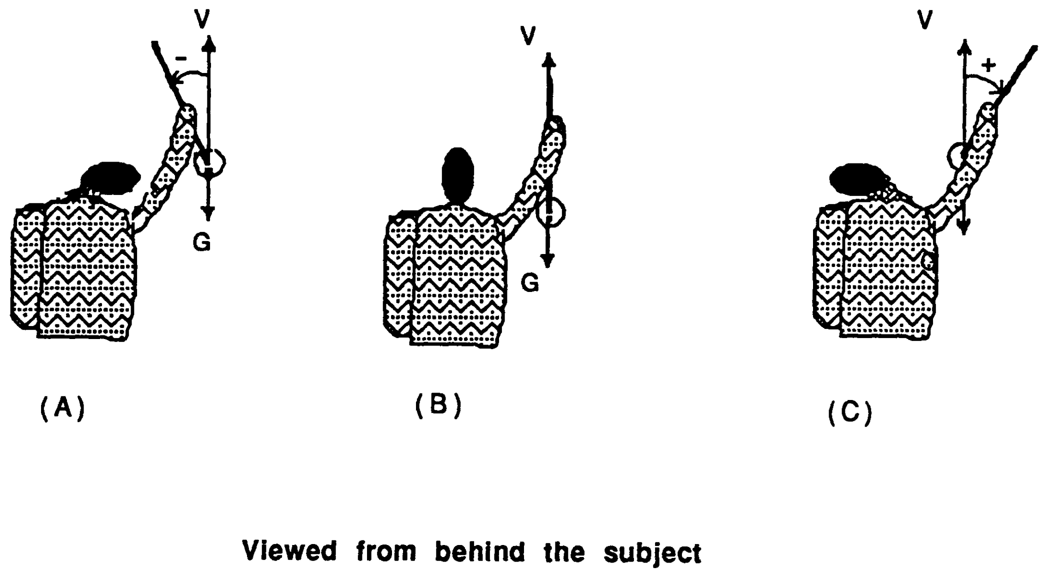


Figure 2.1: Illustration of KSV experiment

dial face into a *vertical frontal-parallel plane.*

A total of six subjects (22–35 years of age, two females and four males) were tested in this experiment. Three of them were right-handed, two were left-handed and one was ambidextrous. Each subject had 10 trials at each head position with the presentation of the head tilts randomized. The randomization was also balanced, i.e. every head position was preceded by each of the other two head positions the same amount of times. For example, head position B was preceded five times by A and C. The experimental design limited the time the subject maintained a tilted head position to about 20 seconds.

There has been much evidence that prolonged head and/or whole body tilts affect the perception or indication of the vertical [6,8,9,38,50,53,54,55]. Wade [53] and Schöne, *et al* [39] reported approximately 8^o adaptation effects with a prolonged 90^o

whole body tilt for 3 and 5 minutes respectively. Wade [53] also found that head tilts tend to have a larger adaptation effect than whole body tilts. Therefore, the adaptation problem could be very large in our experiment if we did not control the duration of the head tilt. Based on the time history of tilt adaptation, from Wade [53], and Mann and Passey [20], the adaptation effect of a 90^o head position in a 20 second duration in our KSV experiment would not exceed 1%, i.e. 1^o. The randomization technique and returning upright after each trial would further minimize this effect.

2.1.2 RP Indicator and Data Recording

The *Rod and Pendulum Indicator* or *RP Indicator* consists of a handle rod, an eccentrically weighted dial, a thumb nut, and a dial lock (see figure 2.2). The dial, pivoted at the bottom end of the rod on a ball bearing, serves as a pendulum. When the dial face is held in a vertical plane, with the thumb nut lifted, the inclination of the rod from the true vertical line (the plumb-line) is indicated on the dial. Releasing the thumb nut locks the dial for datum recording.

The direct reading (in the form of 0^o–360^o) can be converted to a value in the form of 0^o to $\pm 180^o$ to represent the angles between the rod and the vertical. A "+" sign indicates a tilt of the rod from the vertical towards the operating hand while a "-" sign means a tilt in the opposite direction. Suppose a subject uses his right hand for the test. Then a datum of "$+15^o$" means that the *RP Indicator* is tilted 15^o from the vertical towards his right (operating hand side); whereas -17^o indicates that the *RP Indicator* is tilted 17^o towards his left (non-operating hand side) (see also figure 2.1 for sign convention).

2.1.3 Results

The data were divided into three groups according to the three head positions: (A) the head was tilted 90^o to the side of the operating (usually dominant) hand, (B) the head was upright, and (C) the head was tilted 90^o to the side opposite to the operating hand. Table 2.3 contains the mean, variance and the degree of freedom in every subject-head combination. The inter-subject variability is apparent, but so also are some trends in the data. The means of the indication errors for $+90^o$ head tilt (column A) had significant negative values; those for -90^o head tilt (column B) had significant positive values (t-test). But for the upright head position (column B), the signs vary from subject to subject, but the means are also significantly different from zero. This suggests that every subject showed significant indication errors in almost all head positions. The errors were the smallest when the head was upright. The direction of the errors was subject dependent. When the head was tilted to the side, the indication errors were much larger and systematically biased. The indication biases were always in the direction opposite to the tilt of the head (see figure 2.4). These biases are best seen from the differences between the indications when the head was tilted and the control indications (see table 2.5 and figure 2.6). These differences are referred to as *E-effects vs. control.* Take subject # 1 for instance, whose indications were biased from the control 18.89^o counterclockwise when his head was tilted 90^o clockwise, and 16.00^o clockwise when his head was tilted counterclockwise as viewed from behind. The results of the

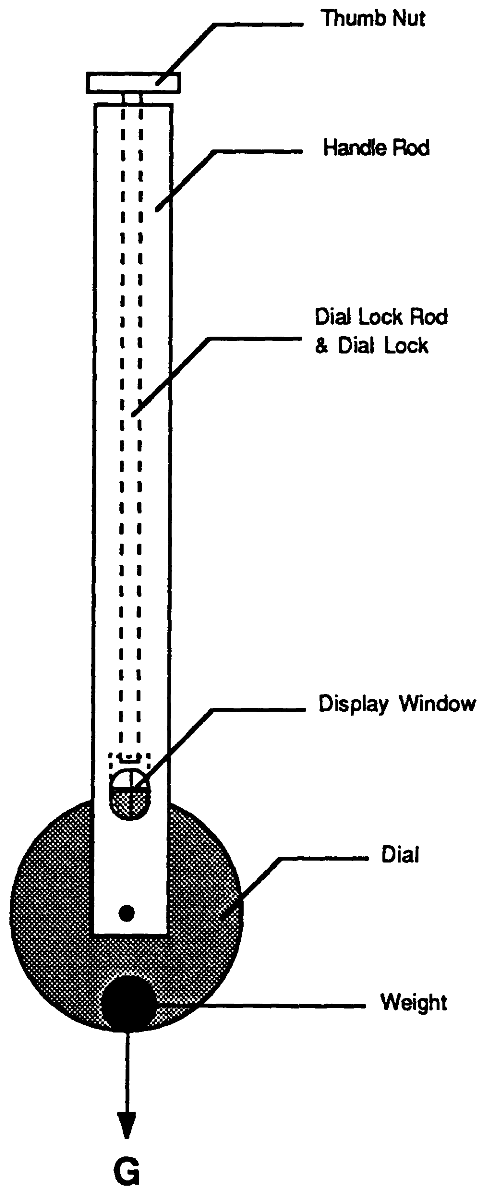


Figure 2.2: Illustration of the *Rod and Pendulum Indicator*

Table 2.3: Means and standard deviations from KSV Experiment

Subjects	Results	Head Positions A(90°)	B(0°)	C(−90°)	Pooled
1	mean	-17.56	1.33	17.33	0.37
	variance	6.03	0.25	5.50	3.93
	df	8	8	8	24
	t	21.45	7.98	22.17	0.97†
2	mean	-21.33	3.33	4.56	-4.48
	variance	7.25	7.00	11.78	8.68
	df	8	8	8	24
	t	23.77	3.78	4.00	7.90
3	mean	-12.89	4.22	12.00	1.11
	variance	12.36	1.19	4.75	6.10
	df	8	8	8	24
	t	11.00	11.61	16.52	2.34
4	mean	-11.56	4.33	7.89	0.22
	variance	6.53	4.75	4.61	5.30
	df	8	8	8	24
	t	13.57	5.96	11.02	0.50†
5	mean	-17.38	-0.56	13.22	-0.97
	variance	20.84	3.78	16.69	13.46
	df	7	8	8	23
	t	10.77	0.86†	9.71	1.35†
6	mean	-12.33	-0.67	7.33	-1.89
	variance	23.50	11.50	9.00	14.67
	df	8	8	8	24
	t	7.63	0.59†	7.33	2.56
Pooled	mean	-15.47	2.00	10.39	-0.94
	variance	12.58	4.75	8.72	8.66
	df	47	48	48	143
	t	29.90	6.36	24.38	3.82

† The t-test result is not significant. All others are significant.

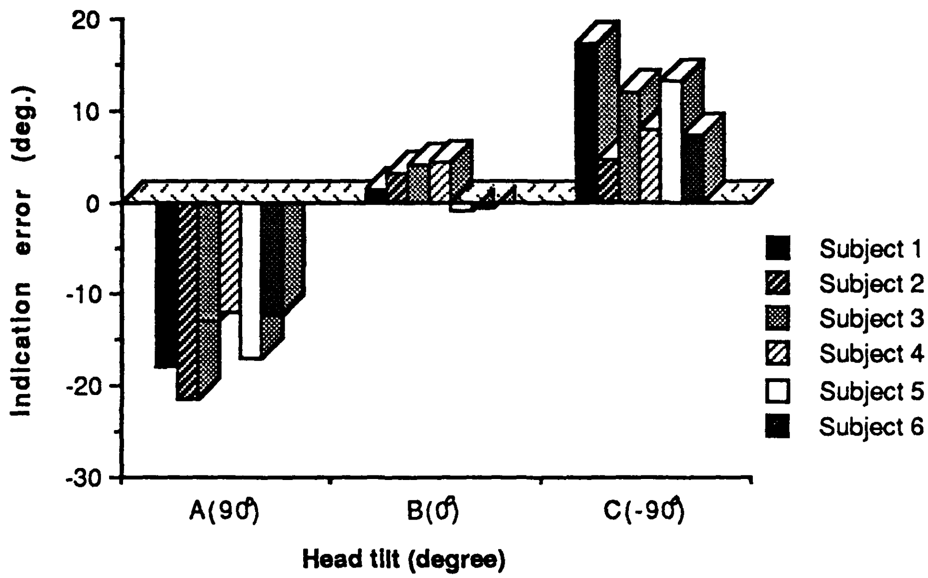


Figure 2.4: Illustration of the subjects' indications of the vertical

Table 2.5: Results of paired t-tests

subject	result	Comparisons A - B	C - B	$\|A\| - \|C\|$
1	mean	-18.89	16.00	0.22
	variance	6.86	5.75	15.94
	df	8	8	8
	t	21.64	20.02	0.50‡
2	mean	-24.67	1.22	16.56
	variance	2.50	19.19	7.78
	df	8	8	8
	t	46.81	0.84‡	53.43
3	mean	-17.11	7.78	0.89
	variance	17.61	4.69	19.86
	df	8	8	8
	t	12.23	10.78	1.80‡
4	mean	-15.89	3.56	3.67
	variance	14.36	7.28	6.50
	df	8	8	8
	t	12.58	3.96	12.94
5	mean	-16.88	13.78	4.38
	variance	24.70	25.69	55.98
	df	7	8	7
	t	9.61	8.16	4.68
6	mean	-11.67	8.00	5.00
	variance	41.50	19.00	30.50
	df	8	8	8
	t	5.43	5.51	8.15
pooled	mean	-17.53	8.39	5.14
	variance	17.78	13.60	22.05
	df	47	48	47
	t	28.50	15.76	7.58
E-effect vs. control†		17.53	8.39	

† see page 29 for definition.

‡ T-test result is not significant. All others are significant.

paired t-tests (table 2.5) showed that the subjects exhibited significant *E-effect vs. control* in both of the head tilted positions. The biases in the A and C head positions were asymmetrical (table 2.5). The indications were biased on the average 5^o more when the head was tilted to the side of the operating hand (A) than to the side of the non-operating hand (C)($p < 0.001$; also see figure 2.6). These asymmetrical

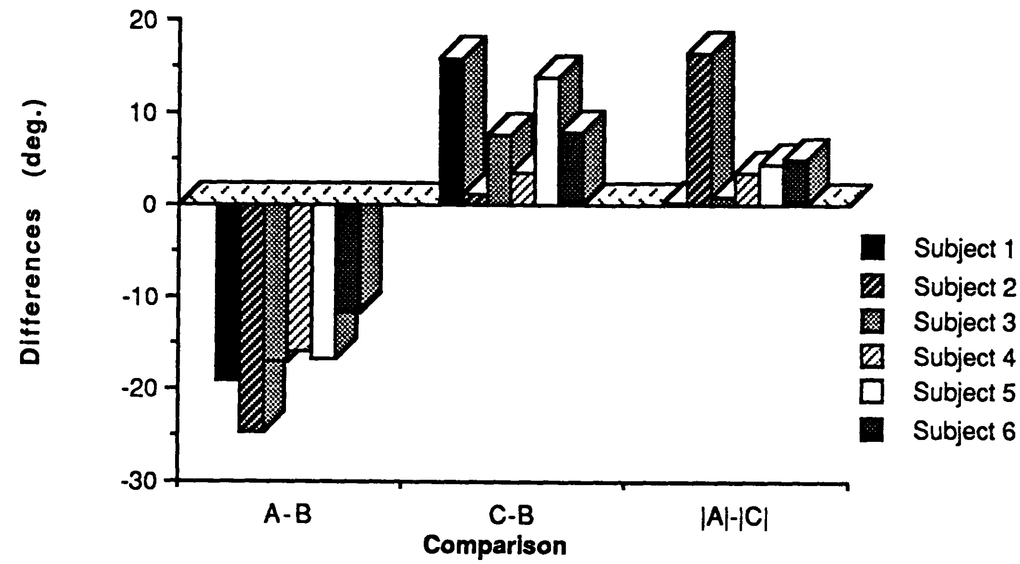


Figure 2.6: Indication errors when compared to the controls

biases were also reflected in the discrepancy between the significant negative grand mean (-0.94^o) and the significant pooled control indication ($+2.00^o$) in table 2.3.

Table 2.7 shows the F-ratio test between the variances in different head positions. Three subjects showed significantly larger variances with the head tilted than with the head upright. The variances in the two head tilt positions were not different

Table 2.7: Results of F-ratio t-tests

Subject	Result	Comparisons		
		A/B	C/B	A/C or C/A
1	F-ratio	24.12	22.00	1.10
	$P_{8,8}$	0.0001*	0.0001*	0.448
2	F-ratio	1.04	1.68	1.63
	$P_{8,8}$	0.480	0.240	0.253
3	F-ratio	10.39	3.99	2.60
	$P_{8,8}$	0.0017*	0.034*	0.099
4	F-ratio	1.37	0.97	1.42
	$P_{8,8}$	0.33	0.517	0.316
5	F-ratio	5.51	4.42	1.25
	$P_{7,8}$	0.018*		0.391
	$P_{7,8}$		0.025*	
6	F-ratio	2.04	1.28	2.61
	$P_{8,8}$	0.167	0.368	0.098
Pooled	F-ratio	2.65	1.84	1.44
	$P_{47,48}$	0.0005*		0.106
	$P_{48,48}$		0.019*	

* F-test is significant.

from each other. The other three subjects (# 2, 4 and 6) also showed the same tendency (table 2.3), but they are not consistent nor statistically significant.

Table 2.8 shows the ANOVA results. They further confirm the inter-subject variability ($p < 0.0001$) and the indication biases imposed by subjects' head tilts ($p < 0.0001$).

Table 2.8: ANOVA results from KSV experiment

Factor	df	Sum of squares	Mean squares	F-ratio	Tail Prob.
Head Position	2	559.38	111.88	10.91	< 0.0001
Subject	5	18383.79	9191.90	896.77	< 0.0001
Interaction	10	1284.21	128.42	12.53	< 0.0001
Model	17	20227.38	1189.85	116.08	< 0.0001
Error	144	1476	10.25		
Adj Total	161	21703.38	134.80		

† This is a two factor crossed design, with both of the factors fixed; therefore all of the F-ratios were calculated by dividing the mean squares of the error (residues) into the corresponding mean squares.

2.1.4 Discussion

Before going into formal discussion, one statement must be made. The ***Aubert-*** and ***Müller-effects*** were both defined relative to the true vertical. In almost all VSV experiments, subjects also showed consistent control indication errors, although with smaller magnitudes, as found in our KSV experiment. Therefore, the conventional method of classifying A- and E-effects always created some inconsistencies. This is especially true with small head and/or body tilts. The author believes that the more appropriate reference is the control indication of the vertical, which is the indication of the vertical when the subject is in the upright position. Therefore, ***A-effects vs. control*** and *E-effects vs. control* can describe the influences of head and/or torso tilts on perception and indications of the vertical in a much more consistent way.

Although A-effects (and usually A-effect vs. control too) were expected, based on Müller's generalization about the A- and E-effects in the visual modality, the results in this experiment are analogous to the E-effect or E-effect vs. control. They actually agree in terms of direction with the results of Bauermeister *et al.* [3] who performed a KSV experiment with the subjects' whole body tilted. In his experiment, the subjects showed "E-effects vs. control" at body tilts of up to $\pm 90^o$. Their results were different from the results in classical VSV experiments; they did not further investigate the cause of the discrepancy and draw people's attention to it. In the very same year, when Bauermeister performed a VSV experiment [2] and obtained the same results as the VSV classical results, they seemed to deliberately avoid discussing the discrepancy. The reason could be that it was difficult to explain the results using their "tonic-field theory of perception".

Based on these KSV results, we can conclude that Müller's generalization holds true only in the visual indication modality (as he intended); the indications of the vertical in the kinesthetic modality are different from those in the visual indication modality, and thus cannot be predicted by Müller's generalization. In the classical VSV indication experiment, A-effects of about 5^o were reported when a subject's head was tilted 90^o sideways. The differences between the E-effects found in our KSV experiment and the A-effects in the classic VSV experiments are on the order of 15^o to 20^o.

In principle, the *perceptions* of the vertical for a particular subject in the two cases (KSV and VSV) should be virtually the same whichever indication modality is involved. Thus the difference observed between the classic VSV and our KSV experiments must arise from the the difference in the way the vertical is indicated. If the difference is attributed to the fundamental differences between the visual and kinesthetic modalities, a seated subject with his head erect would show the same difference (15^o to 20^o) when asked to indicate his perceived inclinations both visually and kinesthetically. Notice that in order to test the fundamental differences, this erect body position was essential. For example, a subject could be asked to set both a visual line (manipulated by someone else) and a rod (manipulated by himself) to the vertical simultaneously, or to set a rod parallel to a visual line, etc.. To investigate this, the latter method was chosen because of its simplicity as described below.

2.2 Inclination Indication with Unseen Hand (IIUH)

2.2.1 Set-up

This experiment utilized a visual line display and a pivoted *RP Indicator* (called *PRP Indicator*; figure 2.9). The *RP Indicator* used in the KSV experiment was held firmly in a pivoting holder mounted to a laboratory stand allowing one degree of freedom–rotation in a vertical plane parallel to a subject's frontal plane. Since the lab stand was clamped onto a bulky table behind the visual display, the indicator was hidden from the subject. The visual line was black, about 2 mm wide, drawn through the center of a 15″ diameter white disk, pivoted at its center, and attached to white cardboard. The white cardboard was attached to a sturdy wooden frame and clamped onto the same table in front of the *PRP Indicator* assembly. The experimenter could place the visual line in any inclination from the vertical by rotating the disk about its center. Two arm holes made below the disk allowed the subject's arms access to the unseen *PRP Indicator*.

2.2.2 Procedure

Three subjects, one female and two male, participated. Subject # 1 and # 2 participated in the KSV experiment (coded subject # 1 and # 3 then) approximately two months ago. The experiment was conducted in a room with normal light. The subject sat erect directly in front of the visual line display and tried to position the unseen *PRP Indicator* parallel to the visual line displays. The subjects' eyes were open during alignment and closed between trials.

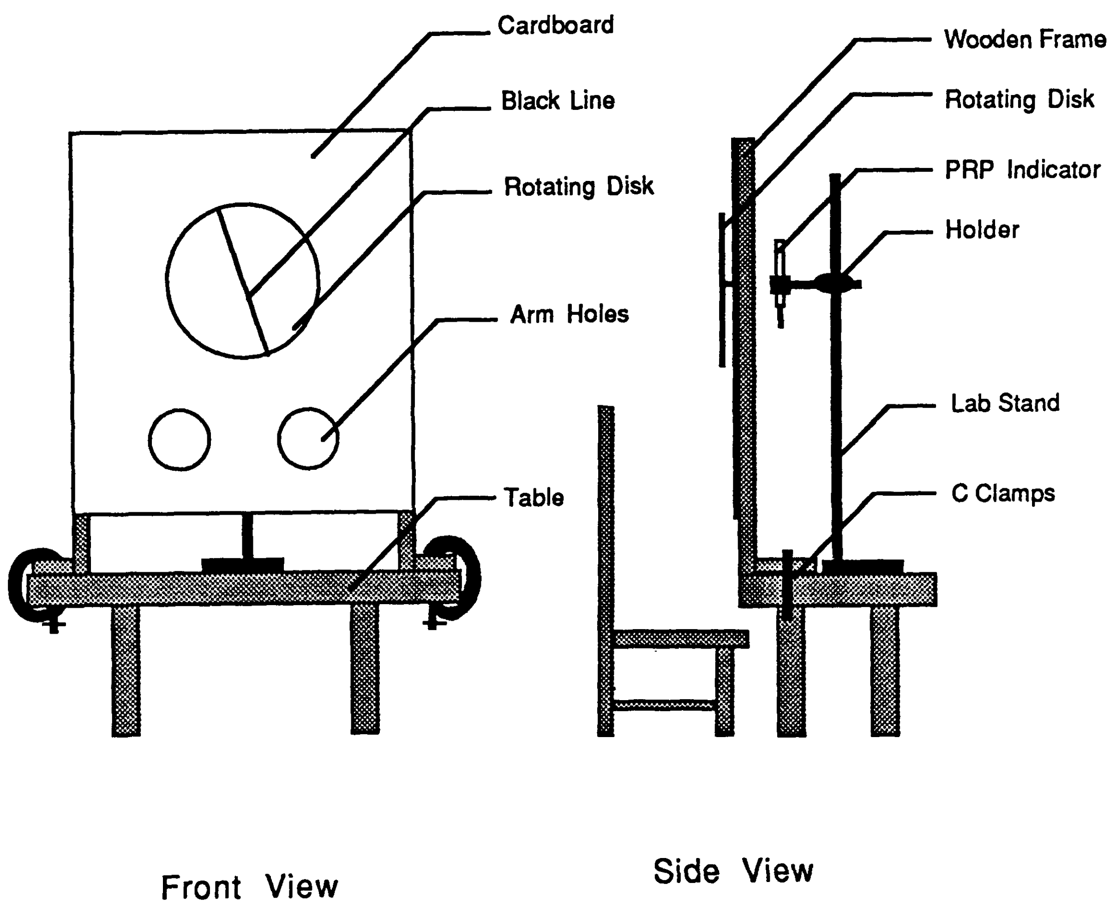


Figure 2.9: Visual display and the unseen PRP Indicator

It has been reported that a tilted line seems less tilted after a period of prolonged inspection and consequently a vertical line seems tilted in the opposite direction [10,12,11,49,57]. These are known as visual line tilt adaptation and its after effect. To minimize these effects, the presentation of the visual line target was randomized. This design limited the time to within 15 seconds for the subject to inspect a particular visual line display at a time, thus restricting the development of the visual line tilt adaptation and its after-effect. Based on the results from Gibson and Radner [12], the tilt adaptation and its after effect should not exceed 0.7^o in this experiment.

The subjects' hand did not touch the *PRP Indicator* at any time except during the trials. After each trial, the position of the *PRP Indicator* was reset randomly to prevent the tactile-kinesthetic tilt adaptation and its after-effect [41,60], and also the effect of initial rod position [57]. At the beginning of each trial, the subject's hand(s) were guided to the *PRP Indicator* without touching the lab stand, so that the vertical lab stand would not give the subject a *hard reference*[2]. The tasks were done with the left or right hand alone, and with both hands.

2.2.3 Results

Table 2.10 shows the group mean indication error in each hand-target combination and the pooled results. Only four of the nine hand-target combinations give

[2]*A hard reference* means a reference formed by an object that a subject knows is vertical or horizontal, such as the lab stand. In this experiment, the lab stand would be a perfect hard reference of verticality for a subject because it was so close to the PRP Indicator. Therefore it was critical not to let a subject's hand touch it.

Table 2.10: Averaged indication errors from IIUH experiment

Target	Results	Operating Hand(s)			Pooled
		A (DH)	B (BH)	C (NDH)	
A' (15°)	Mean:	−2.73°	−3.18°	−1.09°	−2.33°
	Variance:	6.67	6.68	4.10	5.82
	df	8	8	8	24
	t	3.17 **	3.69 **	1.62	4.83 **
B' (0°)	Mean:	−0.90°	0.54°	2.18°	0.63°
	Variance:	15.27	4.73	2.92	7.64
	df	8	8	8	24
	t	0.70	0.75	3.83 **	1.14
C' (−15°)	Mean:	0.54°	0.63°	3.00°	1.39°
	Variance:	5.27	4.77	11.52	7.19
	df	8	8	8	24
	t	0.71	0.87	2.65 *	2.59*
Pooled	Mean:	−1.03°	−0.67°	1.36°	−0.11°
	Variance:	9.07	5.39	6.18	6.88
	df	24	24	24	72
	t	1.71⋆	1.44	2.74 **	0.36

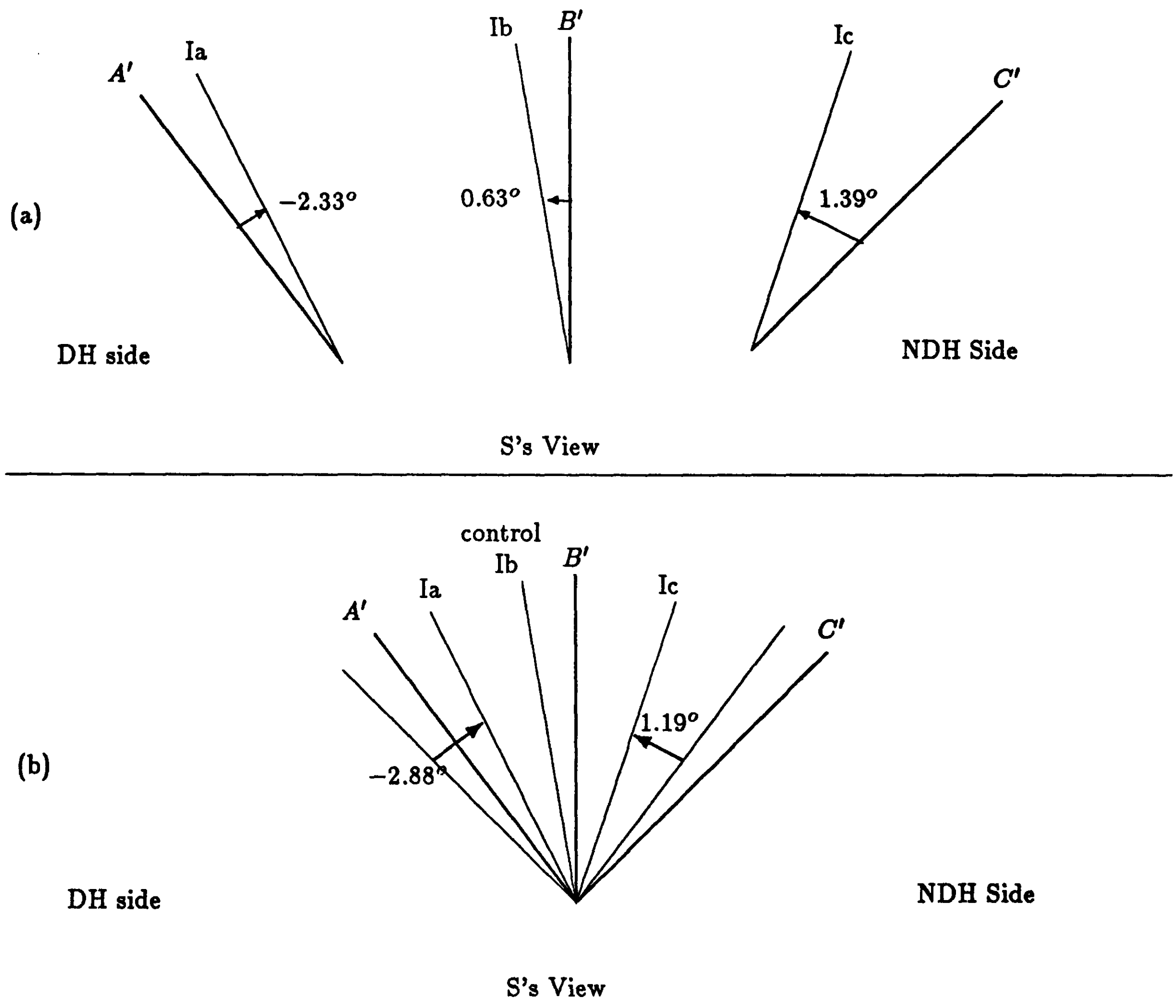
† Three columns A,B,C represent the results of dominant hand, both hands, and non-dominant hand respectively. Three rows A', B', C' represent the results when the visual target was tilted 15° toward the dominant hand, was upright, and was tilted 15° toward the non-dominant hand.

‡ A positive sign means that the indication was biased toward the dominant hand, a negative sign means that the indication was biased toward the non-dominant hand.

⋆ $\alpha = 0.05$ in one tailed t-test.

* $\alpha = 0.05$

** $\alpha = 0.01$



A', B' and C' are the three target positions; Ia, Ib and Ic are the three indications of the three corresponding targets.

Figure 2.11: Under-indication of inclined visual targets

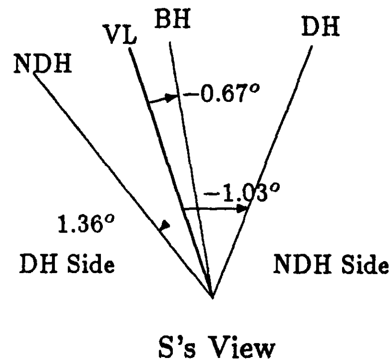


Figure 2.12: The indication biases toward the non-operating hands (pooled results across visual line targets)
VL: Visual-Line; BH: setting with Both-Hands which is also referred to as control; DH: setting with Dominant Hand and NDH: setting with Non-Dominant Hand.

mean indication errors that are significantly different from zero (t-test). Therefore, these tests do not yield any consistent indication bias in the subjects' performances. But the indication errors always have negative means for $+15^o$ tilted target (row A') and positive means for -15^o tilted target (row C'). This suggests that the subjects' indications were tilted from the target toward the non-dominant hand side (negative indication error) when the line was tilted towards the dominant hand side ($A', +15^o$; $p < 0.01$ when pooled across operating hands), and that the indications were tilted from the target toward the dominant hand side (positive indication error) when the target was tilted towards the non-dominant hand side ($C', -15^o$; $p < 0.05$ when pooled across operating hands) (see figure 2.11 (a)). Therefore, subjects tended to under-indicate the two 15^o tilted visual lines A' and C' ($p < 0.05$ and $p < 0.01$ respectively).

The effect of the operating hand (column effect in table 2.10) is not quite as clear as the effect of the line position (row effect). The indication errors do not vary systematically; as reflected by the signs of the means of indication errors. But, it seems that the indication errors were more consistently indicated toward the non-dominant hand when the operating hand was the dominant hand, and toward the dominant hand when the operating hand was the non-dominant hand. The results of t-test applied to pooled means showed that the effect of the operating hand(s) was significant ($p < 0.01$ and $p < 0.05$; table 2.10). Therefore, we infer from this that the subjects tended to bias their indications in the direction of the non-operating hand (also see figure 2.12).

ANOVA test (table 2.13) also showed that operating hands ($p < 0.003$) and line positions ($p < 0.0001$) had strong effects although the results varied significantly among the subjects ($p < 0.005$).

2.2.4 Discussion

This experiment showed that the subjects systematically under-indicated the tilt of the $\pm15^o$ tilted visual lines. This may correspond to the well-documented characteristic of a subject's unwillingness to go to extremes in estimation [17,25,31,40].

Instead of showing an approximate 15^o–20^o bias between a visual display and the kinesthetic indication as was hoped, this experiment suggested that the visual and kinesthetic indication were in good agreement, especially when both hands were used (only 0.11^o grand mean error).

Another finding was that the subject's indications were biased towards the non-

Table 2.13: Results of F-test in IIUH Experiment

Source	df	Sum-squares	Mean-squares	F-ratio‡	Tail Prob.
Sub†	2	368.04	184.02	16.07	0.0045
Hand	2	87.61	43.81	6.37	0.0028
VL	2	292.33	146.17	21.25	< 0.0001
Sub×VL	4	143.43	35.86	5.21	0.0010
Sub×Hand×VL	8	91.64	11.45	1.66	0.1232
Error	72	495.33	6.88		

† Sub: subject; Hand: operating hand; VL: visual line; ×: interaction

‡ This is a three factor nested/crossed design: Hand and VL are crossed and are further nested within Sub. Both Sub and VL are fixed factors. Therefore F-ratios are calculated as following: $F(Sub)_{2,8} = \frac{ms(Sub)}{ms(Sub\times Hand\times VL)}$, $F(Hand)_{2,72} = \frac{ms(Hand)}{ms(Error)}$, $F(VL)_{2,72} = \frac{ms(VL)}{ms(Error)}$, $F(Sub \times VL)_{4,72} = \frac{ms(Sub\times VL)}{ms(Error)}$ and $F(Sub \times Hand \times VL)_{8,72} = \frac{ms(Sub\times Hand\times VL)}{ms(Error)}$.

operating hand (within about 2^o) when compared to the control (both hands). The bais is believed to be caused by the asymmetrical neuro-muscular activities created by using a single hand for indication. This means that asymmetrical muscular involvement could induce kinesthetic indication bias. This also suggests that it might be the asymmetrical neuro-muscular activities that caused the discrepancy between the KSV and the classical VSV experiments.

Note that the basic indication bias in our KSV experiment was toward the side of the operating hand (2^o on average). It is opposite to the bias found here. The difference might be related to the fact that the RP Indicator was not restricted in the KSV experiment but was pivoted in the IIUH experiment.

Re-examining the results of the KSV experiment, one can see that when a subject's head was upright, the vertical indication was offset by only 2.0^o. This is on the order of the error of the visual vertical indication in the upright head positions found in classical VSV experiments that have been reported [7,12,16,18,19,28,58]. Therefore the real issue is the discrepant occurrences of the A- and E-effects in the KSV and classical VSV experiments. But the discrepancy occurred only when the subject's head was tilted.

At this point, the next step was very clear. Virtually the same IIUH experiment should be conducted, but with the subject's head tilted. In order to better correlate with VSV experiments, the next experiment was designed in a slightly different way. Instead of testing a subject with a black line display in a normally bright room, a luminous line display in an otherwise dark room was used. Because the subjects complained that the handle rod of the *PRP Indicator* was too short to have a clear feeling of its tilt and that the pivot did not offer adaquate resistance to work against when turning, a new indicator was constructed which had a longer rod and larger rotation friction. The following section describes this *Visual-Kinesthetic Spatial Inclination Matching* experiment (in short VKSIM).

2.3 Visual Kinesthetic Spatial Inclination Matching. I. head tilted 90^o to the side

2.3.1 Luminous Line Display and Rod Indicator

The display facility was built using a wooden frame, a light source assembly and a black cardboard disk with a 2 mm wide and 2 foot long slit through its center (see figure 2.14). The light source assembly was a slender, transparent plastic block with two flash light bulbs mounted at both ends and powered by a DC power supply (figure 2.14 (b)). It was firmly glued on the back of the black cardboard disk, and was taped over with black tape so that the only visible light emitted was from the slit in the disk. By adjusting the output of the power supply, a dim and uniform luminous line was achieved. The disk was able to rotate about its center so that the luminous line could be set at any inclination.

The *Rod Indicator* was constructed using a potentiometer, a digital voltmeter, a ± 15 volt power supply and a 10 inch long, three-fourth inch diameter thick aluminum rod (see figure 2.15). The rod was balanced and pivoted at its center onto the rotating nut of the potentiometer. When the rod was rotated from the vertical, the angular deviation was reflected by the digital voltmeter display, which was converted to the real angle after calibration. Figure 2.16 illustrates the readout circuitry.

2.3.2 Procedure

Two male subjects, aged from 23 and 26 were tested. Subject # 1 participated in the KSV experiment (coded subject # 2 there) about two months before, and subject

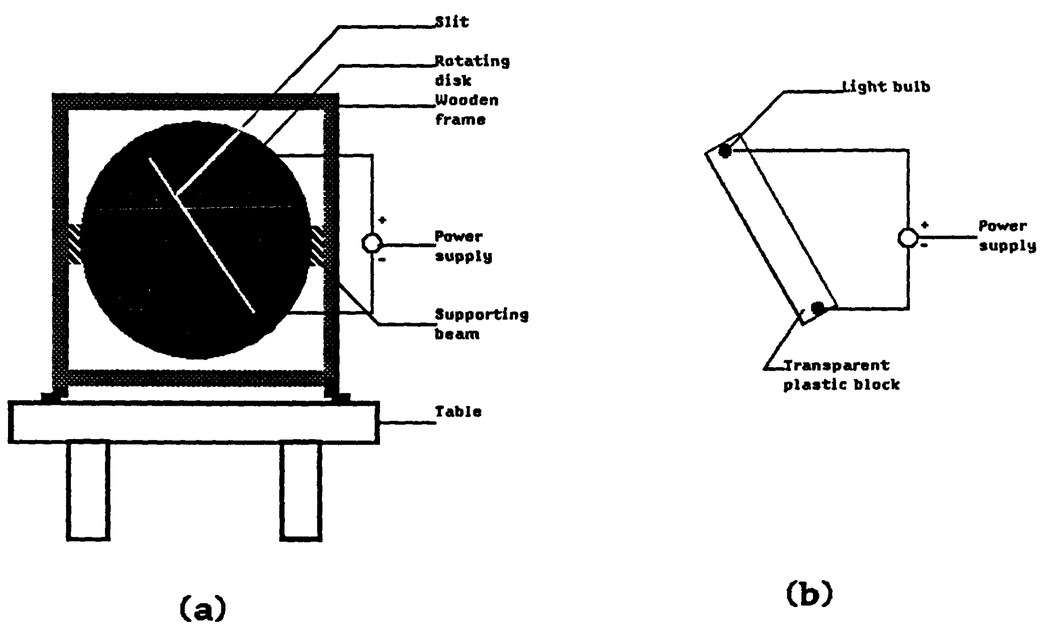


Figure 2.14: Luminous line display

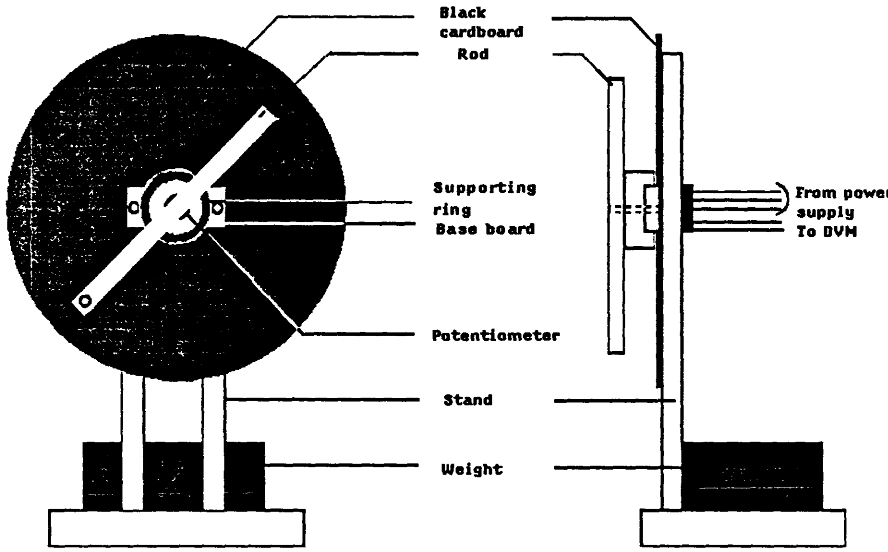


Figure 2.15: Illustration of *Rod Indicator*.

The potentiometer is firmly mounted on the aluminum base board. The rod was securely assembled onto the rotating nut of the potentiometer. A small hole is drilled at one end of the rod to tell a subject to keep the corresponding end lower than the other when he sets the rod. The supporting ring supports the undesirable torque in the front-back direction to protect the potentiometer. It also constrains the movement of the rod in a fronto-parallel plane.

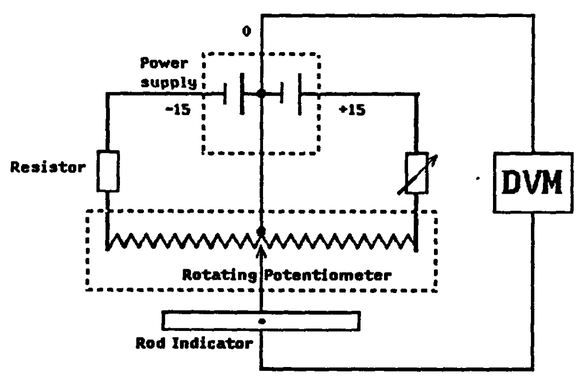


Figure 2.16: Circuitry for the readout system

2 participated in the IIUH experiment (coded subject # 3 there) about two weeks before. The subjects were asked to use both hands to set the ***Rod Indicator*** parallel to a luminous line display. Three visual target positions were used, each at three different head positions. These three visual target positions were vertical, inclined 15^o to the left, and inclined 15^o to the right; the three head positions were upright, head tilted 90^o left, and head tilted 90^o right. The head was kept completely in the horizontal position in the two latter cases. Notice that, as mentioned in the KSV experiment, a pure head tilt cannot exceed about 45^o; therefore, a 90^o head tilt requires that both the torso and the head being tilted. The presentation of both the visual line displays and head positions were randomized to minimize the effect of tilt-adaptations (both visual line tilt-adaptation [10,11,12,49,57] and head-tilt-adaptation [5,6,8,9,38,39,50,52,54,55]) and their after effects. The subject had 30 seconds to inspect a particular visual line or maintain a particular head tilt at a time. As discussed on page 20, the head tilt adaptation effect for a 90^o tilt of 20–30 seconds would be approximately 1^o. Based on the results from Gibson and Radner [12], the visual line tilt adaptation effect in this experiment should not exceed 0.7^o. The after effects were further minimized by blindfolding the subject and returning the subject to the upright head position for about 15 seconds after every trial.

To avoid the potential influence of the initial rod position [57], a subject was instructed to rotate the rod toward and beyond the ***candidate setting position***[3] by about 10^o, and then back three times before making the final setting. This also

[3] *A candidate setting position* means the position a subject would set the rod to match a visual line display if he had set the rod in his first move.

gave the subject more time to circumvent the rapid transient disturbance otolith inputs caused by the head tilts. To prevent the kinesthetic tilt adaptation and its after-effect [41,60], the indicator was reset randomly after each trial.

The subject's primary gaze changes when he tilts his head. In the upright, his primary gaze is approximately at the center of the luminous line, but when the head is tilted, the primary gaze moves with the head. Thus looking at the center of the luminous line requires an oblique gaze of the subject. According to Listing's law [13], the oblique gaze would induce an apparent tilt of the luminous line [13,27,32]. To minimize this problem the display facility was moved 7 feet away from the subject. This reduced the angle of the oblique gaze when the head was tilted. If the horizontal and vertical translational displacements of the head were both 1 foot when the head was tilted, then the induced visual tilt would be approximately 0.58 degrees[4]. This level is tolerable for this experiment.

The *Rod Indicator* was at the subject's chest level directly in front of him. Therefore the subject was facing the *Rod Indicator* and the luminous line display which was 7 feet away. To reduce the physical awkwardness of indicating when the head was tilted, the subject was seated in a rolling chair. He could slide left and right to accommodate himself to the fixed *Rod Indicator*. This also compensated partially for the oblique gaze problem. Both the visual display and the indicator were in vertical planes parallel to the subject's frontal plane relative to his head (roll planes).

[4]See Robinson, 1963 for detail. The formula used here is $\Psi = sin^{-1}(\frac{sin\theta sin\phi}{1+cos\theta cos\phi})$, where Ψ is the approximation of the induced visual tilt; θ and ϕ are the vertical and horizontal gaze angles respectively.

The room had to be completely dark to keep objects in the room from serving as hard visual references (see footnote on page 33), and to keep the subject from seeing the shadows of the *Rod Indicator.* Otherwise the experiment would not have been a visual-kinesthetic matching test as intended. To keep the rod from casting shadows when moved into the foreground of the luminous line, a black piece of cardboard was placed behind the rod (see figure 2.15).

There was also the problem of *dark adaptation.* In order to prevent the subject from adapting to the dark, the room lights were switched on after each trial. During the light-on periods, the subject's eyes were loosely blindfolded or closed to allow some light to enter his eyes while not allowing him to see any object in the room. The scattering light could prevent him from adapting to the dark, and he could not refresh his sense of verticality.

2.3.3 Results

The subjects' indication errors are illustrated in figure 2.17. In these diagrams, the subjects' indication errors (in degree) are plotted vs. the head tilt for each session, each subject, and each target. When in the upright position, both subjects exhibited considerable indication errors. When their heads were tilted, both subjects showed enormous indication biases in both sessions. Although the magnitudes varied between sessions and subjects, the directions were always the same for the same head tilt (A or C). When the head was tilted toward the side of the dominant hand (A), the bias was toward the side of the non-dominant hand (negative error); when the head was tilted toward the side of the non-dominant hand (C), the bias was toward

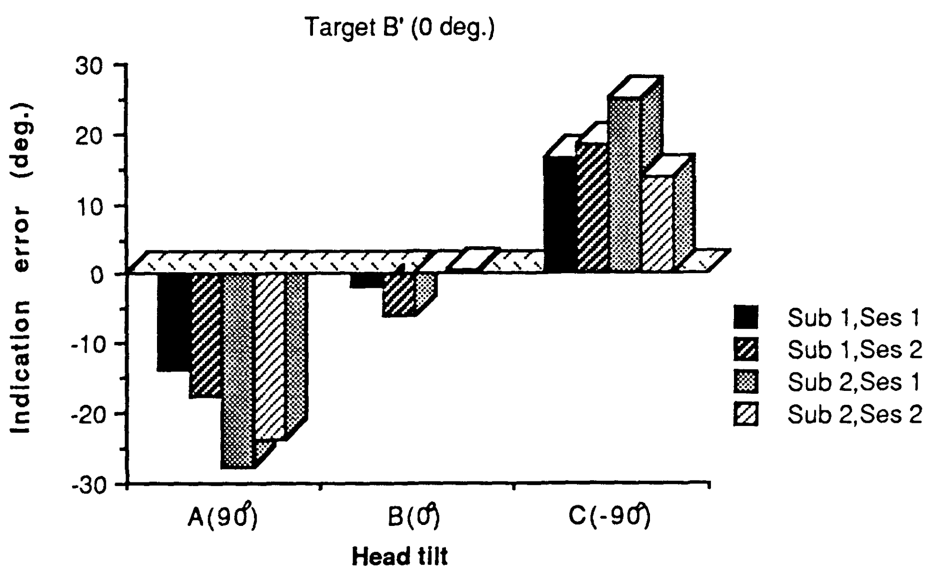
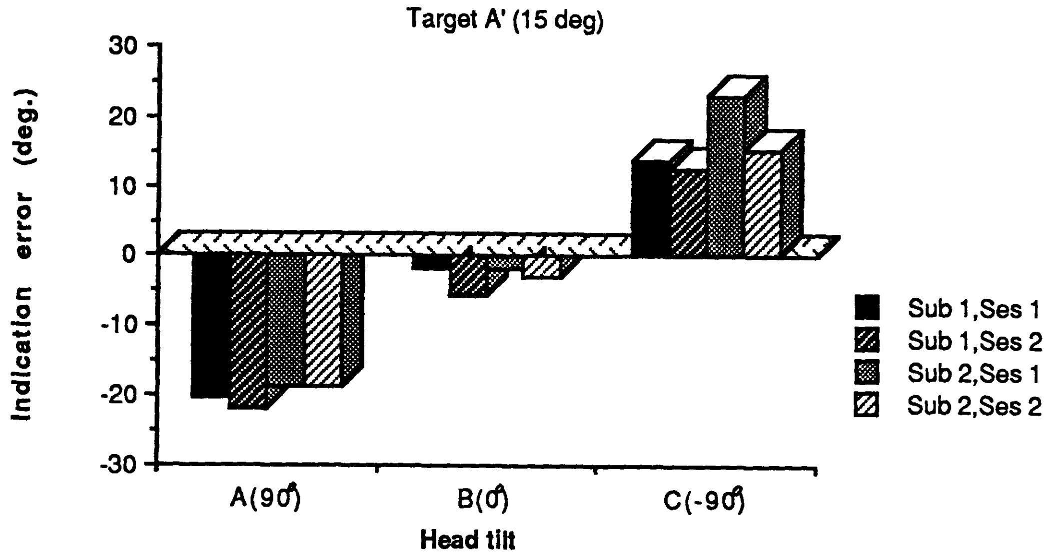


Figure 2.17: Effect of the head tilt on the subjects' indications (continued ...)



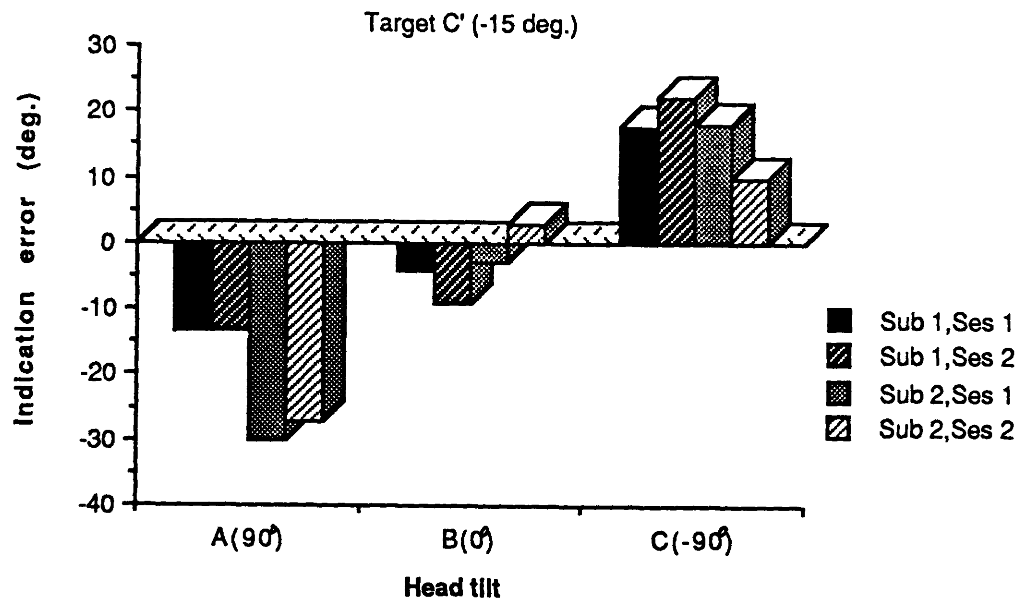


Figure 2.17: Effect of the head tilt on the subjects' indications (End)

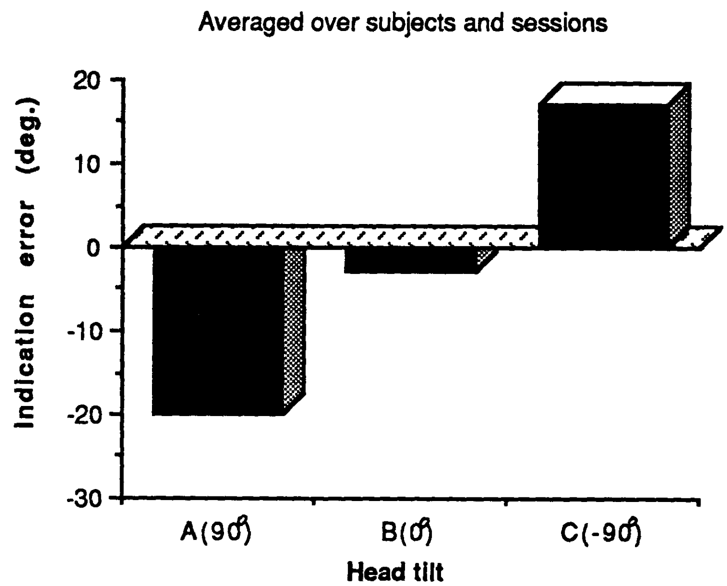


Figure 2.18: Effect of the head tilt on the subjects' indications. (Averaged over subjects, sessions, and targets)

the side of the dominant hand (positive error). In other words, the indications were biased in the direction opposite to the side of the head tilt.

In spite of the significant intersubject and intersession differences, the averaged results still represent this remarkable effect very well (see figure 2.18 and 2.19). Therefore, the pooled results will be used for statistic analysis of the head tilt.

Table 2.20 shows the group results of the indication errors (deviations of the hand settings from the true positions) in each head-target position combination. The t-tests show that the means in all of the head-target combinations, the pooled means and the grand mean are all significantly different from zero. The pooled means of

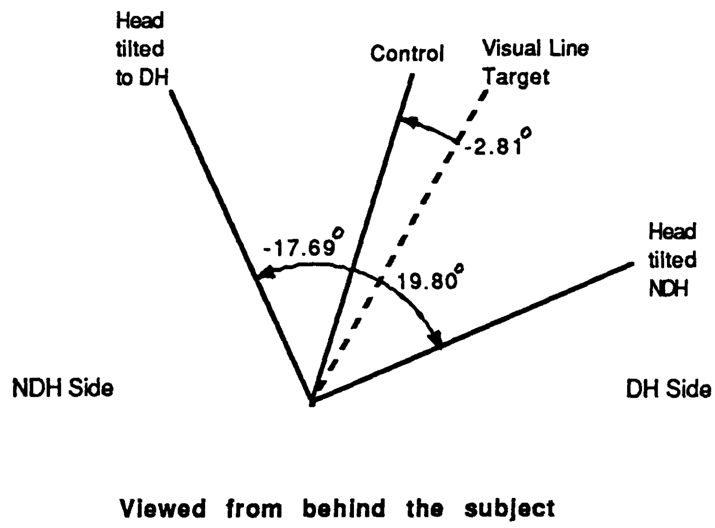


Figure 2.19: Indication bias in the direction opposite to the head tilts

the two head tilted positions (-20.49^o and 17.00^o) are about 20^o apart from that (-2.81^o) of the control head position (upright). This suggests an indication bias of about 20^o in the direction opposite to the head tilt. This is better illustrated by comparing the indication errors for tilted and upright conditions. The mean differences (along with the paired t-test results) are given in table 2.21. The indication differences between head positions A(90^o) and B(0^o) all have significant negative values; whereas those between C(-90^o) and B(0^o) all have significant positive values. This means that the subjects' indications were biased toward non-dominant hand (negative values) with the head tilted toward dominant hand (A), and that the indications were biased toward dominant hand (positive values) with the head tilted toward non-dominant hand (C). Thus, this supports the observation from table 2.20 that, when compared to the control (head upright), the indications of the vertical

Table 2.20: Mean indication errors in VKSIM.I (with head tilted)

Target	Result	Direction of head tilts			Pooled
		A(90°)	B(0°)	C(−90°)	
A' (15°)	Mean	−20.05°	−3.38°	15.97°	−2.49°
	Variance	18.52	2.48	18.96	13.32
	df	16	16	16	48
	t	19.21	8.85	15.12	4.78
B' (0°)	Mean	−20.86°	−1.77°	18.12°	−1.50°
	Variance	25.98	3.29	8.22	12.50
	df	16	16	16	48
	t	16.87	4.02	26.06	2.97
C' (−15°)	Mean	−20.56°	−3.27°	16.90°	−2.31°
	Variance	10.98	8.65	9.57	9.73
	df	16	16	16	48
	t	25.58	4.58	22.52	5.18
Pooled	Mean	−20.49°	−2.81°	17.00°	−2.10°
	Variance	18.49	4.81	12.24	11.85
	df	48	48	48	144
	t	33.36	8.97	34.01	7.35

† Three columns A, B, C represent the results when a subject's head was tilted toward his dominant hand, upright, and tilted toward his non-dominant hand, respectively. Three rows A', B', C' represent the results when the visual target was tilted toward the dominant hand, upright, and tilted away from the dominant hand.

‡ A positive value means an indication bias toward dominant hand; a negative value means an indication error toward non-dominant hand.

* All the t-test values are significant at 95% or higher confidence level.

Table 2.21: Indication biases imposed by head tilts

Target	Result	Comparisons	
		$A - B$	$C - B$
A' (15^o)	Mean	-16.67^o	19.35^o
	Variance	14.11	12.77
	df	16	16
	t	18.30	22.33
B' (0^o)	Mean	-19.09^o	19.89^o
	Variance	25.70	14.23
	df	16	16
	t	15.53	21.74
C' (-15^o)	Mean	-17.30^o	20.16^o
	Variance	18.89	19.63
	df	16	16
	t	16.41	18.76
Pooled	Mean	-17.69^o	19.80^o
	Variance	19.57	15.54
	df	48	48
	t	27.99	35.16

$t_{16,0.99} = 2.92$, $t_{48,0.99} = 2.69$

Mean: the mean of the differences between the indication errors of A and B, C and B.

were biased by about 20^o toward the side opposite to the head tilt.

The following depicts the results in more detail.

Case B': a vertical target

Subjects showed biases of -19.09^o for tilts toward dominant hand and $+19.89^o$ for tilts toward non-dominant hand in addition to a control bias of -1.77^o (see figure 2.22).

Case A': a target tilted 15^o to dominant hand

A -16.67^o bias was found when the head was tilted toward the dominant hand and $+19.35^o$ when tilted toward the non-dominant hand (see figure 2.23). The control bias was -3.38^o.

Case C': a target tilted 15^o to non-dominant hand

A -17.29^o bias was imposed by a tilt of the head toward dominant hand, $+20.17^o$ by a tilt toward non-dominant hand, in addition to a control bias of -3.27^o (figure 2.24).

Table 2.20 also suggests that the indication variabilities were larger when the head was tilted than was upright. This is further confirmed by the F-test results as shown in table 2.25.

ANOVA also suggested that the performances differed from subject to subject (two subjects, $p = 0.033$) and from session to session ($p < 0.003$). The contribution

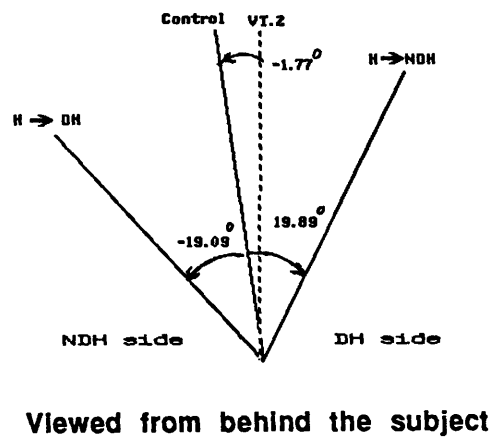


Figure 2.22: Case B': bias with a vertical target

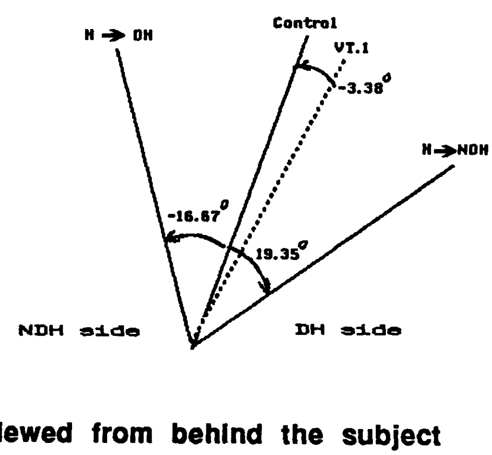


Figure 2.23: Case A': bias when target was tilted 15^o toward dominant hand

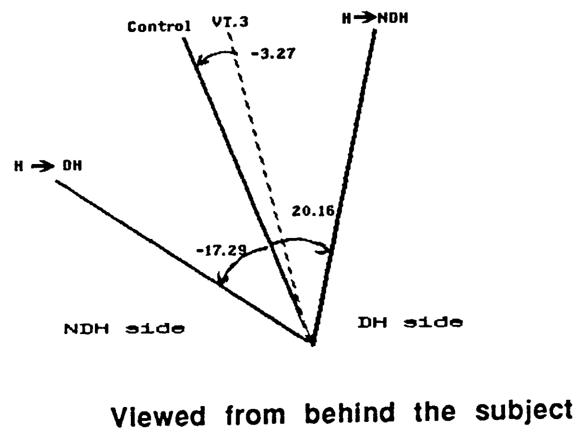


Figure 2.24: Case C': bias when target was tilted 15^o toward non-dominant hand

Table 2.25: Results of F-test between group variances

Target	Result	Comparisons		
		A/B	C/B	A/C
A'	$F_{16,16}$	7.47	7.65	1.02
(15^o)	p	0.0001	0.0001	0.48
B'	$F_{16,16}$	7.90	2.50	3.16
(0^o)	p	0.0001	0.04	0.01
C'	$F_{16,16}$	1.27	1.11	1.15
(-15^o)	p	0.32	0.42	0.39
Pooled	$F_{48,48}$	3.84	2.54	1.51
	p	0.0001	0.0008	0.08

to the variance from the effect of the head position is striking ($p < 0.0001$).

Table 2.26: F-test of Results from VKSIM.I with head tilted

Source	df	Sum-squares	Mean-squares	F-ratio	prob > f
Ses	1	53.784	53.784	4.54	0.033
Sub	1	106.856	106.856	9.02	0.003
HT	2	42197.32	21098.66	1780.77	< 0.0001
VL	2	33.096	16.548	1.40	0.249
Sub×HT	2	1022.336	511.168	43.14	< 0.0001
Sub×VL	2	514.773	257.386	21.72	< 0.0001
Ses×HT	2	136.315	68.157	5.752	0.004
Error	144	1706.121	11.848		

Ses: Session; Sub: Subject; HT: Head tilt; VL: Visual line tilt; ×: interaction.

One suprising result is that the interaction between the subject and the visual target is very signifcant ($p < 0.0001$). Meanwhile, the subject effect is barely significant ($p < 0.03$) and the target effect is not significant at all ($p = 0.249$; table 2.26). This suggests that the subjects might have the opposite trends vs. the target tilt in their indications. The indication errors of the three targets were -4.09^o, -0.79^o and $+0.22^o$ respectively for subject # 1, but were -0.88^o, -2.22^o and -4.84^o for subject # 2. They indeed change in the opposite directions. ANOVA performed on individual subjects showed that the effect of the visual target positions is significant for both subjects ($p < 0.0001$ for subject # 1 and $p < 0.001$ for subject # 2; see table 2.27 and table 2.28). This means that subject # 1 tended to under-indicate the tilt of the inclined targets (when compared to the control), and that subject # 2 tended to over-indicate the tilt of the inclined targets.

Table 2.27: Results of F-test on subject # 1

Source	df	Sum-squares	Mean-squares	F-ratio	$p > F$
Ses	1	53.65	53.65	5.94	0.016
HT	2	17146.00	8573.00	949.69	<0.0001
VL	2	304.40	152.20	16.86	<0.0001
Ses×HT	2	155.34	77.67	8.60	0.001
Ses×VL	2	24.22	12.11	1.34	0.267
HT×VL	4	312.87	78.22	8.66	<0.0001
Ses×HT×VL	4	36.04	9.03	1.00	0.585
Error	72	649.96	9.03		

Ses: Session; HT: Head tilt; VL: Visual line tilt; ×: interaction.

Table 2.28: Results of F-test on subject # 2

Source	df	Sum-squares	Mean-squares	F-ratio	$p > F$
Ses	1	53.27	53.27	3.63	0.057
HT	2	26073.35	13036.67	888.90	<0.0001
VL	2	243.39	121.69	8.30	0.001
Ses×HT	2	658.25	329.13	22.44	<0.0001
Ses×VL	2	37.40	18.70	1.27	0.285
HT×VL	4	434.99	108.75	7.41	<0.0001
Ses×HT×VL	4	66.08	16.52	1.13	0.351
Error	72	1055.96	14.67		

Ses: Session; HT: Head tilt; VL: Visual line tilt; ×: interaction.

Another surprising result is that the inter-session variability was larger than the inter-subject variability. When we examine the data carefully, we found that subject # 1 showed more consistent intersession differences, whereas subject # 2 showed larger but less consistent inter-session differences. But the ANOVA tests performed on individual subjects suggested that the intersession difference was significant for subject # 1 ($p < 0.02$) but not for subject # 2 ($p = 0.057$). Actually the two subjects had about the same intersession mean-squares of errors (53.65 for subject # 1 and 53.27 for subject # 2). The reason why subject # 2 failed to show significant intersession difference was that he had a larger residue error mean square (14.67 as opposed to 9.03 for subject # 1; see table 2.27 and 2.28).

2.3.4 Discussion

Cross modality matching was first used extensively by Stevens and others [42,43,44,45,46,47] in perception estimations. In their experiments, the subjects were asked to match two seemingly uncomparable stimuli at the same intensity level— such as the brightness of light and the loudness of sound. It is harder to imagine how that match was achieved in the CNS, but subjects showed some consistent results. It is certainly easier to assume that a subject is able to match a visual line and a rod in the same inclination. In the VKSIM.I experiment the subjects were actually matching the two perceived inclinations of the visual line and the rod. This is expressed in the simple block diagram shown in figure 2.29.

In this experiment, the matching is achieved by changing the physical position of the Rod Indicator. The process enclosed in the broken line is also called the

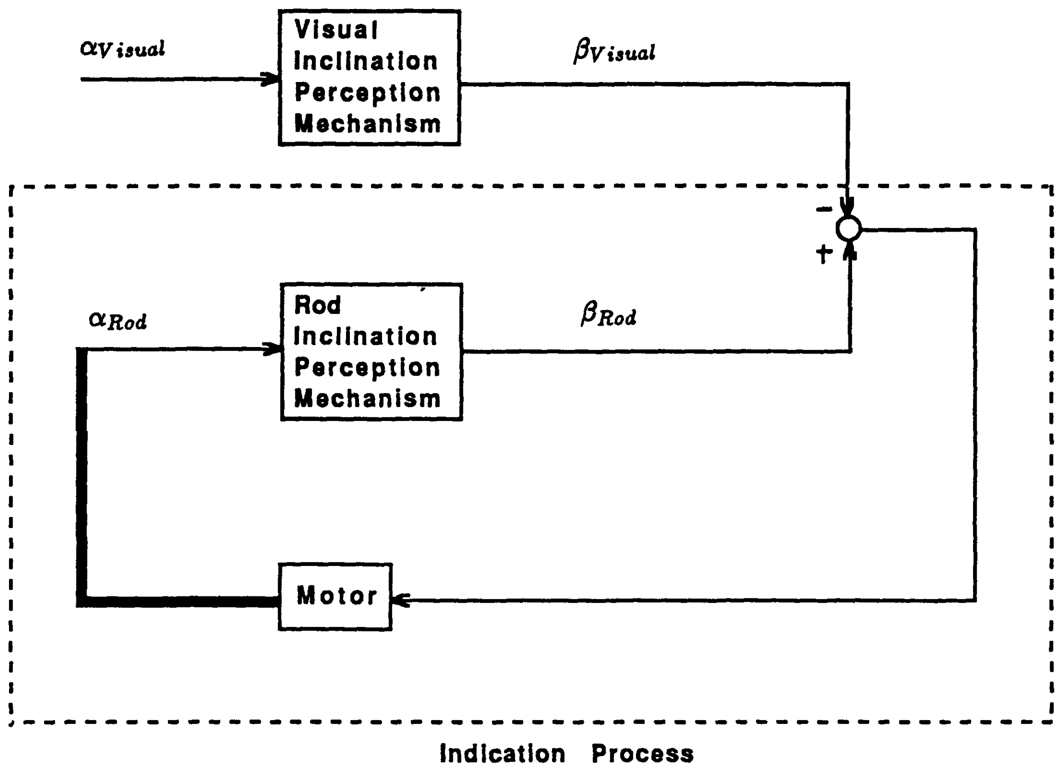


Figure 2.29: Block diagram of VKSIM.
α_{Visual}: physical tilt of the visual line display; α_{Rod}: physical tilt of the Rod Indicator; β_{Visual}: perceived tilt of the visual line display, serves as a psychological reference input; β_{Rod}: perceived tilt of the Rod Indicator.

Indication Process. It includes perceiving the inclination of the indicator, comparing the perception with the *psychological reference input* and the manipulation of the indicator until the matching between the perceptual and the psychological reference input is reached. In the case of VKSIM.I, the psychological reference input is the perceived inclination of the visual line. Although this process is referred to as an indication process, the key is still the perception of the indicator's inclination.

When the matching is reached, the visual line (or visual target) and the Rod Indicator have the same internal or psychological representation (referred to as an *Internal Inclination*).

$$\text{Physical Inclination of the Visual Line } (\alpha_{Visual})$$
$$\Longleftrightarrow \text{ Internal Inclination } (\beta) \Longleftrightarrow$$
$$\text{Physical Inclination of the Rod Indicator } (\alpha_{Rod})$$

The symbol "$\Longleftrightarrow$" should be read as "is associated with". It means that the physical inclinations of the Visual line (α_{Visual}) and the Rod Indicator (α_{Rod}) have the same Internal Inclination (β). The physical inclination of the Rod Indicator is also referred to as a VKSIM indication.

From the results of the IIUH and these VKSIM.I experiments, we know that the relationships between the α_{Visual} and α_{Rod} vary with the tilt of the head/torso and the position of the visual line display.

The two subjects in this experiment showed different tendencies vs. the tilts of the targets. One subject showed under-indication when indicating the two tilted targets. The other one showed the opposite tendency (exaggeration) instead. This shows how great the difference between subjects can be.

But the main effect, the effect of the tilt of the head/torso, is consistent for both subjects. When the head and torso were upright (control condition), the VKSIM error was only about 3^o, i.e.

$$(\alpha_{Rod})_{control} \doteq \alpha_{Visual} - 3^o$$

But when the subjects' head was tilted $\pm 90^o$ (left or right), the VKSIM indications were systematically biased by an amount of approximately 20^o when compared to the control, i.e.

$$\alpha_{Rod} \doteq (\alpha_{Rod})_{control} \pm 20^o$$

The bias has a positive sign when the tilt of the head/torso was toward the non-donminant hand (-90^o) and a negative sign with the tilt toward the dominant hand (90^o).

Since the above relation was approximately true for all the three visual displays used, it should also be true for any visual line display in the range of $\pm 15^o$ from the vertical. One of these displays would correspond to a zero Internal Inclination, i.e. the Subjective Vertical. Let V_V and V_K denote the physical inclinations of the visual line and Rod Indicator that are perceived as vertical, then we have that for a 90^o head/torso tilt

$$V_V \Longleftrightarrow 0^o \text{ (Subjective Vertical)} \Longleftrightarrow V_K$$

$$V_K = (V_V - 3^o) \pm 20^o$$

V_V and V_K are referred to as the *Visual Vertical* and the *Kinesthetical Vertical* respectively. The equations state that the Kinesthetical Vertical V_K is offset from the Visual Vertical V_V by approximately 20° opposite to the tilt of the head/torso when compared to the control. This is also illustrated in figure 2.30.

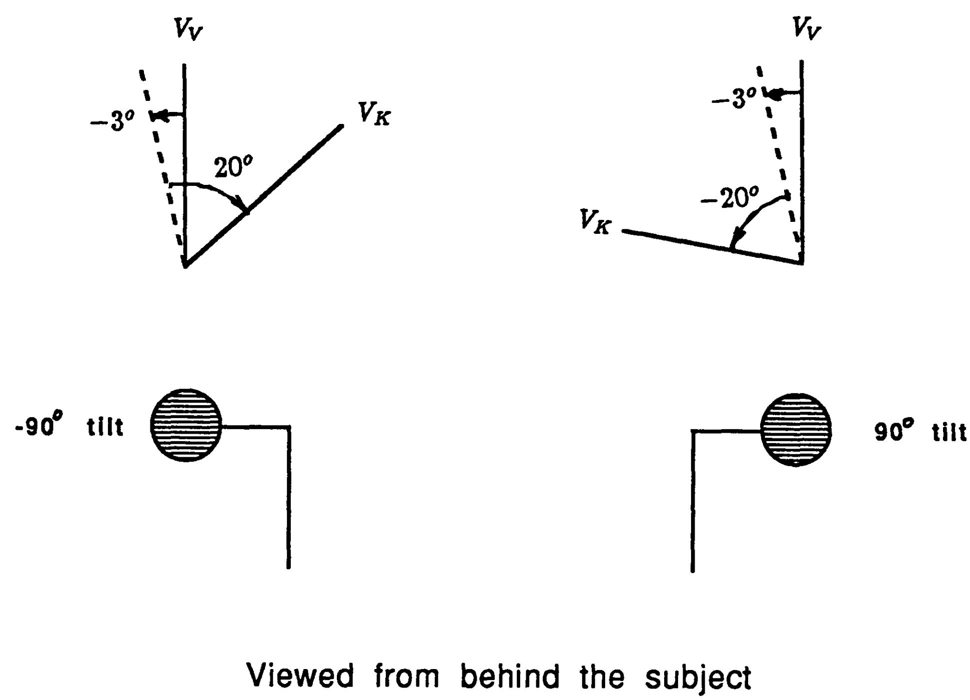


Figure 2.30: Relationship between the Visual and Kinesthetical Verticals.

The broken lines represent the control kinesthetic vertical, i.e., the kinesthetic indication of the vertical when a subject sits upright.

The VSV and KSV indications are also matching tasks. The VSV or KSV indication process is actually a matching between the Subjective Vertical and the perceived inclination of the visual line or the Rod Indicator. In order to indicate the vertical, the indicators (a visual line or a rod) must be perceived as vertical. Therefore, for the same head/torso tilt, the VSV indication (I_{VSV}) should have the same relationship with its Subjetive Verticals (SV_{VSV}) as that V_V has with SV_{VKSIM}, i.e.,

$$I_{VSV} - SV_{VSV} = V_V - SV_{VKSIM}$$

And for the same head/torso tilt, the KSV indication (I_{KSV}) should have the same relationship with its Subjetive Verticals (SV_{KSV}) as that V_K has with SV_{VKSIM}, i.e.,

$$I_{KSV} - SV_{KSV} = V_K - SV_{VKSIM}$$

Subtracting these two equations yields the following:

$$(I_{KSV} - I_{VSV}) - (SV_{KSV} - SV_{VSV}) = V_V - V_K$$

Therefore, if the difference between the VSV and KSV indications is the same as that between V_V and V_K, we can conclude that the Subjective Verticals in the VSV and KSV experiments are the same. Although we do not have any solid evidence for the premise, the results in the classical VSV experiments (5^o of A-effect) and our KSV experiment (15^o of E-effect) suggest that it may be true for a 90^o head tilt. Therefore, it is reasonable to postulate that the perceptions of the vertical or SV are the same in VSV and KSV experiments and that the indication discrepancy was caused by the indication processes. This means that the seemingly contradictory A-effect in the classical VSV experiment, and E-effect in our KSV experiment, are actually consistent in terms of vertical perception.

We also know that the KSV indication has a much larger bias than the VSV indication. Therefore, it is probably fair to assume that the kinesthetic modality is responsible for a major portion of the VKSIM indication bias and that only a small portion of it is produced by the visual modality. We will discuss this aspect in more detail in the next chapter.

There is another very important issue that we have not addressed. It is the relationship between a head tilt and a whole body tilt.

As mentioned in the introduction, *A- and E-effects* were originally introduced by Müller in visual verticality perception/indication studies with only the subject's head tilted. Later researchers have extended the usage of these two terminologies to experiments with the subjects' entire body tilted. It has been widely accepted, explicitly or tacitly, that head tilts and whole body tilts are basically equivalent in human spatial orientation. This assumption was probably due to some reported similar results in visual verticality indications [2,23]. But are they really the same? To have a rough idea, one only needs to examine the magnitudes of the kinesthetic E-effects in our KSV experiment (head tilted) and Bauermeister's KSV experiment (whole body tilted) [3]. It is on the order of 15^o in ours but only about 3^o in Bauermeister's at the 90^o tilt. Therefore it seems likely that the tilt of the head and the whole body have at least different degrees of effect on the subject's kinesthetic verticality indications, although it is unclear whether the differences come from the perception, the indication, or both. Differences in the procedures and the equipmen could also contribute to the discrepancy.

If the differences originated from the indication process, then it should be reflected in a test similar to VKSIM.I, but with the subject's whole body tilted horizontally. In other words, if a subject is asked to align a rod parallel to a visual line display when his whole body is tilted horizontally, his indication should be biased. The bias should have a magnitude sufficient to account for the 3^o E-effect in Bauermeister's experiment. To determine how big this bias (from now on referred to as VKSIM bias) should be, one only needs to compare this result with the results reported in his VSV experiment. In that experiment [2], an A-effect of about 12^o was found in the VSV indications with the subjects' entire body tilted to the horizontal position. Therefore the magnitude of the VKSIM bias should be about 15^o to account for the discrepancy between Bauermeister's VSV and KSV results and between his and our KSV results. In the following experiment, a subject was asked to set the *Rod Indicator* parallel to a luminous line when his entire body was tilted 90^o (horizontal body position).

2.4 VKSIM.II–with whole body tilted

2.4.1 Procedure

This test used the same visual displays as in the previous one, but different body postures. Instead of tilting the head, the subject lay on a horizontal table on his left or right side with his head in straight alignment with his torso. His head was supported to reduce tension on the neck muscles which might influence the perception of the head positions (see figure 2.31). For testing convenience, 15 trials

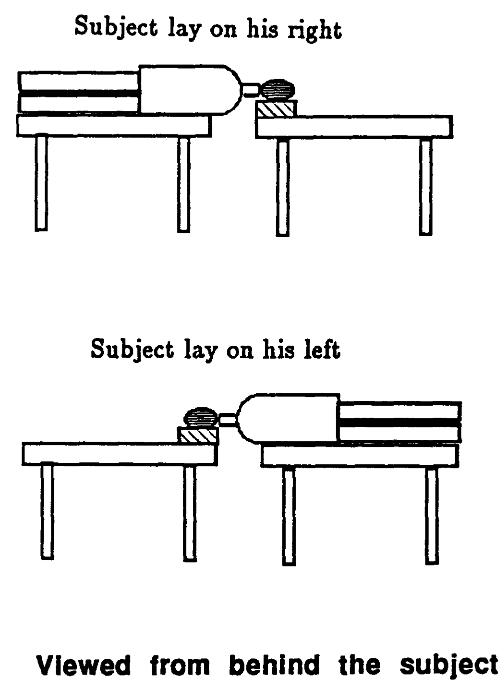


Figure 2.31: Test conditions in VKSIM.II

in each body position (containing 5 randomized trials for each of the three visual line targets) were tested in a row. The test lasted for about 10 minutes in each body position. In order to circumvent the initial transient state, a subject stayed in each test position for about two minutes prior to the start of that particular test. As in the previous experiment, both hands were used for indication.

2.4.2 Results

Due to time constraints, only one subject and one session was conducted in this preliminary experiment. The male subject, age 26, participated in both KSV (coded subject # 2 then) and VKSIM.I (coded subject # 1 there) experiments. The results are shown in table 2.33 – 2.35.

Figure 2.32 shows the subject's mean indications in each body-target combination. Table 2.33 shows the means, variances and the pooled results. Seven of the means in the nine target-head combinations are not statistically different from zero; nor are the two pooled means in the horizontal body positions (column D and F). This means that this subject did not show significant indication error when the entire body was in the horizontal positions.

On the other hand, the pooled mean in the body upright position, (column E) is significantly different from zero, indicating that the subject's indications with the body upright are biased toward his non-dominant hand side ($p < 0.01$). This means that the subject's indications were more accurate when his whole body was horizontal than when his whole body was upright. Obviously, the whole body tilts did influence the indications. The paired t-tests between the signed indication errors when the whole body was tilted, (D and F), and when it was upright, (E), also

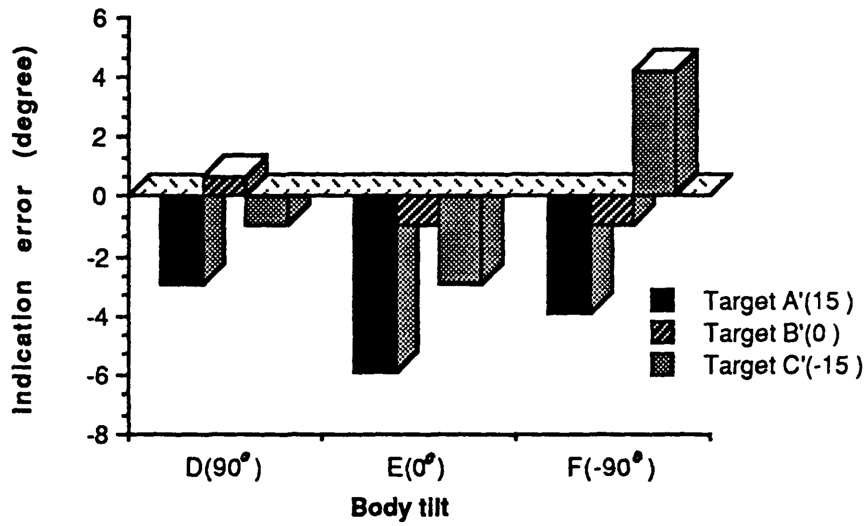


Figure 2.32: Illustration of the subject's indications

Table 2.33: Averaged indication errors from VKSIM.II with whole body tilted

Target	Result	Direction of body tilts			Pooled
		D(90°)	E(0°)	F(−90°)	
A' (15°)	Mean	−3.10°	−6.16°	−4.28°	−4.52°
	Variance	5.52	9.50	13.08	9.37
	df	4	4	4	12
	t	2.95*	4.47*	2.56	5.32**
B' (0°)	Mean	0.65°	−0.67°	−1.44°	−0.49°
	Variance	5.85	5.21	6.99	6.02
	df	4	4	4	12
	t	0.60	0.66	1.22	0.72
C' (−15°)	Mean	−0.81°	−3.17°	4.19°	0.07°
	Variance	16.32	12.38	15.79	14.83
	df	4	4	4	12
	t	0.45	2.01	2.36	0.07
Pooled	Mean:	−1.09°	−3.34°	−0.51°	−1.65°
	Variance	9.23	9.03	11.95	10.07
	df	12	12	12	36
	t	1.29	4.01**	0.53	3.16**

* $\alpha = 0.05$ ($t_{4,0.05} = 2.78$; $t_{12,0.05} = 2.18$)

** $\alpha = 0.01$ ($t_{4,0.01} = 4.60$; $t_{12,0.01} = 3.06$; $t_{36,0.01} = 2.72$)

† D: The subject lay on his dominant hand side (90°); E: The subject sat upright (0°); F: The subject lay on his non-dominant hand side (−90°).

support this observation (table 2.34).

Table 2.34: Differences in indication errors between body positions

Target	Result	Differences D − E	F − E	D − F
A' (15°)	Mean	3.06°	1.88°	1.18°
	Variance	11.54	5.46	5.34
	df	4	4	4
	t	2.01	1.80	2.31
B' (0°)	Mean	1.32°	−0.76°	2.08°
	Variance	5.75	13.17	5.00
	df	4	4	4
	t	1.23	0.47	2.08
C' (−15°)	Mean	2.36°	7.36°	−5.00°
	Variance	17.87	3.34	19.39
	df	4	4	4
	t	1.25	9.01**	2.54
Pooled	Mean:	2.25°	2.83°	−0.58°
	Variance	11.72	7.32	9.91
	df	12	12	12
	t	2.37*	3.77**	0.66

* $\alpha = 0.05$ ($t_{4,0.05} = 2.78$; $t_{12,0.05} = 2.18$)

** $\alpha = 0.01$ ($t_{4,0.01} = 4.60$; $t_{12,0.01} = 3.06$)

† D: The subject lay on his dominant hand side (90°); E: The subject sat upright (0°); F: The subject lay on his non-dominant hand side (−90°).

A comparison between the two horizontal body positions (column D-F in table 2.34) indicates that there is no significant difference between the indication errors in these two positions; i.e. the direction of the whole body tilts did not significantly influence the indication as did the head tilts in VKSIM.I. This is also seen in the mean differences between the horizontal body positions and the upright (2.25° in column D − E and 2.83° in F − E in table 2.34). In other words, the whole

Table 2.35: F-test of indication errors from VKSIM.II with body tilted

Source	df	Sum-squares	Mean-squares	F-ratio	prob > f
BT	2	87.593	43.797	2.73	0.077
VL	2	237.461	118.731	7.4	0.002
BT×VL	4	87.368	21.842	1.36	0.266
Error	36	577.836	16.051		

BT: Body tilt; VL: Visual line target tilt; ×: interaction.

Table 2.36: Results of paired t-tests between target positions

Comparison	Result	Directions of body tilts			Pooled
		D(90°)	E(0°)	F(−90°)	
$A' - B'$	Mean	−3.75°	−5.49°	−2.85°	−4.03°
	Variance	15.83	11.91	27.07	18.27
	df	4	4	4	12
	t	2.11	3.56*	1.22	3.40**
$C' - B'$	Mean	−1.46°	−2.50°	5.63°	0.56°
	Variance	14.56	26.32	3.74	14.87
	df	4	4	4	12
	t	0.86	1.09	6.51**	0.52
$\|A'\| - \|C'\|$	Mean	−2.29°	−2.99°	−8.47°	−4.58°
	Variance	20.16	36.98	44.61	33.91
	df	4	4	4	12
	t	1.14	1.11	2.84*	2.84*

* $\alpha = 0.05$ ($t_{4,0.05} = 2.78$; $t_{12,0.05} = 2.18$)
** $\alpha = 0.01$($t_{4,0.01} = 4.60$; $t_{12,0.01} = 3.06$) † D: The subject lay on his dominant hand side (90°); E: The subject sat upright (0°); F: The subject lay on his non-dominant hand side (−90°).

body tilts of 90^o to the left and the right seemed equivalent in terms of VKSIM-indications. The F-test also failed to show any consistent influence of whole body tilts upon the indication errors (p=0.077; table 2.35).

When the visual line target was tilted 15^o toward the subject's dominant hand (A'), the indications were biased in the direction of non-dominant hand (negative pooled bias -4.52^o; see table 2.33). This indicates that the subjects tended to under-indicate the 15^o inclined target. When the target was tilted 15^o toward the non-dominant hand (C'), there was no significant indication error (table 2.33). But F-tests show consistent influences of the visual line targets (p=0.002) (table 2.35). Table 2.36 shows the results of the paired t-tests between the indication errors in different target positions. The results are significant between A' and B', $|A'|$ and $|C'|$.

Examining the means pooled over the target positions (column pooled) in table 2.33, one can infer that the indications were more biased toward the non-dominant hand side (the means are more negative -4.52^o, -0.49^o and 0.07^o). This is also supported by the significant negative grand mean (-1.65^o) in the same table (table 2.33).

2.4.3 Discussion

This test clearly indicates that the head tilts and the whole body tilts have different effects upon kinesthetic verticality indications. However it did not yield the 15^o bias (as a consequence of a whole body tilt) needed to explain the 3^o E-effect in Bauermeister's KSV experiment. We can therefor say that the discrepancy between Bauermeister's VSV and KSV experiments cannot be explained by *this one subject's* VKSIM-indications (with his whole body tilted). But we still can not eliminate the possibility that the discrepancy was partially attributed to the differences in the indication methods.

This experiment is not exactly the same as Bauermeister's. The subjects were different and we only sampled one subject. The methods of tilting subjects were also dramatically different: in Bauermeister's KSV experiment, subjects were constrained in a tilting device and could be rotated into any position, possibly without knowing it. But in our experiment, the subject simply lay on a horizontal table and he clearly knew that his body was in the horizontal position. Another important condition which differed from Bauermeister's was the long period of time the subject stayed in every body position in our experiment, and that our subject preadapted 2 minutes in each body position. It is possible that some tilt adaptation occurred in this time.

On the other hand, one important finding is that the left and right whole body tilts were statistically equivalent (when both of the hands were used for indication). There are two possible explanations for this. The first is that the position of the visual line positions relative to the body rather than that of the body relative to gravity are the determining factor of the VKSIM.II indication errors. In this test, there was a 180° directional change of the gravity vector relative to the body between the two horizontal body positions. But the relative positions between the visual line displays and the body positions were practically the same, i.e. the visual line displays were 75^o, 90^o and 105^o tilted from the body in both horizontal positions. The results showed no significant indication difference associated with the 180^o directional change. On the other hand, the direction of the gravity vector relative to the body changed only 90^o between the horizontal and the upright body positions. But the relative positions between the visual line displays and the body were altered. They were 0^o and $\pm 15^o$ with the body upright. Meanwhile there were indication differences between the horizontal and the upright body positions (see table 2.37).

Table 2.37: Differences between the test conditions and results

Between conditions	Changes of gravitational relative to the body	Changes of Visual Line relative to the body	Difference of indications
D to F	180^o	0^o	0^o
D or F to E	90^o	90^o	2.25^o–2.83^o

† D: The subject lay on his dominant hand side (90^o); E: The subject sat upright (0^o); F: The subject lay on his non-dominant hand side (-90^o).

Those differences could be associated either with the changes of the visual lines relative to the body, or the change of the gravity vector relative to the body. The latter argument is less straightforward. Since the 180^o directional change of the gravity vector did not effect the indications, we must ask, why should the 90^o change? The former association is more easily-made. In the horizontal body positions, the visual line displays were about perpendicular to the body axis (in a range of $\pm 15^o$). The two arms were both at the side of the body and were about equally involved in the process of indication. In terms of this, the two horizontal body positions were about the same; therefore, the indications in those positions were not significantly different from each other. But in the upright body position the visual lines were nearly aligned with the body axis (in the range of $\pm 15^o$), (one hand at the top of the rod was at chest level and the other at the bottom of the rod was at stomach level). Thus the two arms were not in symmetrical positions relative to the body. These asymmetrical arm positions inevitably require uneven neuromuscular involvement of the two arms. These uneven neuromuscular activities could conceivably generate an indication bias responsible for the indication differences between the horizontal and upright positions (the rational will be discussed in the following chapter). This suggests that the relative position between the rod and the body was the determining factor. Therefore, when asked to set the *Rod Indicator* parallel to a visual line in the vicinity ($\pm 15^o$) of the horizontal, an upright subject should show approximately the same indications as in positions D and F of this experiment. The following VKSIM.III experiment investigates this. To make a comparison with VKSIM.I, the head tilted positions were also tested in the following VKSIM.III experiment.

2.5 VKSIM.III–with horizontal visual line targets ($\pm 15^o$)

2.5.1 Procedure

In testing conditions which were identical to those in VKSIM.I, a subject's task was to position the *Rod Indicator* parallel to a visual line, at the horizontal or tilted $\pm 15^o$ from the horizontal.

The three head positions were upright, tilted 90^o left, and tilted 90^o right and were represented in a randomized order, as were the three target positions. The randomization was the same as in VKSIM.I.

The same subject as in VKSIM.II (coded subject # 1 in VKSIM.I and VKSIM.II and # 2 in KSV experiment) was tested in this experiment.

2.5.2 Results

Figure 2.38 illustrates the subject's mean indication errors in all head-target combinations. Table 2.39 shows the means of the indication errors with variances and also the pooled results. In order to verify the easily-made assumption discussed in the last section, we hope to find that the subject's indications in that position are the same as those found in positions D and F in VKSIM.II. Therefore, we are most interested in the results in column B. In this position, the means of the indication errors are significantly different from zero for two visual line targets, as is the pooled mean (column B). The subject showed substantial negative indication errors for all three visual line displays. The indications are actually similar to the indications

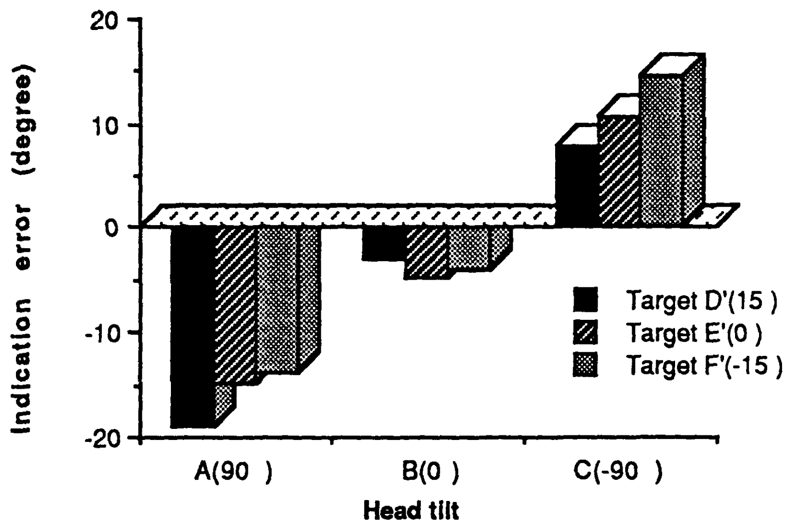


Figure 2.38: Illustration of the subject's indications

made when the same subject was in the upright position in VKSIM.II (table 2.33). Therefore, it is unlikely that this error was due to the asymmetrical postures of the hands as speculated earlier (see section 2.3.4).

Table 2.39: Averaged indication errors from VKSIM.III

Target	Result	Direction of head tilts			Pooled
		A(90°)	B(0°)	C(−90°)	
D' (15°)	Mean	−18.85°	−3.26°	7.82°	−4.76°
	Variance	9.13	14.35	8.60	10.69
	df	4	4	4	12
	t	13.95**	1.92	5.96**	5.25**
E' (0°)	Mean	−15.03°	−5.03°	10.46°	−3.20°
	Variance	12.54	5.04	6.42	8.00
	df	4	4	4	12
	t	3.54*	5.01**	9.23**	4.08**
F' (−15°)	Mean	−14.03°	−4.49°	14.44°	−1.36°
	Variance	7.74	3.57	1.72	4.34
	df	4	4	4	12
	t	11.28**	5.31**	24.62**	2.35
Pooled	Mean:	−16.20°	−4.46°	10.73°	−3.11°
	Variance	9.80	7.65	5.58	7.68
	df	12	12	12	36
	t	18.66**	5.81**	16.38**	6.83**

* $\alpha = 0.05$ ($t_{4,0.05} = 2.78$, $t_{12,0.05} = 2.18$, $t_{36,0.05} = 2.03$)

** $\alpha = 0.01$ ($t_{4,0.01} = 4.60$, $t_{12,0.01} = 3.06$, $t_{36,0.01} = 2.72$)

† D': Visual line tilted 15° clockwise from horizontal; E': visual line in horizontal; F': visual line tilted 15° counter-clockwise from horizontal.

Table 2.40 shows comparisons between the three body positions in VKSIM.II and the upright body position in this experiment (where D, E and F represent the three body positions in VKSIM.II, and B means the upright position in VKSIM.III). With the control visual line displays (B', E'), the indication errors are significantly

Table 2.40: T-test between mean indication errors in VKSIM.II and VKSIM.III.

		Comparisons		
Target	Results	D - B	E - B	F - B
A', D'	Mean	0.08	1.33	0.44
(15°)	*df*	8	8	8
B', E'	Mean	3.85	3.05*	2.31*
(0°)	*df*	8	8	8
C', F'	Mean	1.85	0.74	0.74
(−15°)	*df*	8	8	8
pooled	Mean	2.96*	0.99	3.21*
	df	24	24	24

* $\alpha = 0.05$ ($t_{8,0.05} = 2.31$, $t_{24,0.05} = 2.06$)

** $\alpha = 0.01$ ($t_{8,0.01} = 3.36$, $t_{24,0.01} = 2.80$)

† In VKSIM.II, D: The subject lay on his dominant hand side (90°); E: The subject sat upright (0°); F: The subject lay on his non-dominant hand side (−90°).

different between case E and B, and case F and B. But the *overall* difference is significant between both D and B, and F and B, and not significant between E and B. This suggests that the use of the visual line targets in the vicinity (±15°) of the vertical or horizontal does not produce significant overall indication differences when the body/head are in the upright positions (column E-B in table 2.40). The VKSIM-indications with a luminous line in the vicinity of the vertical while the body is in the horizontal (D, F) is different from those with a luminous line in the vicinity of the horizontal while the body is upright (B). Therefore, it is clear that the relative positions between the visual line displays and the body are not the determining factor of the VKSIM.II indication errors.

Now let us compare the results obtained in VKSIM.I and VKSIM.III. The subject

Table 2.41: F-test of Results from VKSIM.III

Source	df	Sum-squares	Mean-squares	F-ratio	prob > f
HT	2	5445.29	2722.65	354.47	0.0001
VL	2	86.89	43.44	5.66	0.007
HT×VL	4	96.91	24.23	3.15	0.0255
(Model total	8	5629.09	703.64	91.61	0.0001)
Error	36	276.51	7.68		
Total	44	5905.60	134.22		

HT: Head tilt; VL: Visual line target tilt; ×: interaction.

Table 2.42: Results of F-test between group variances

		Comparisons		
Target	Result	A/B	C/B	A/C
A', D'	$F_{4,4}$	1.57	1.67	1.06
(15°)	p	0.34	0.32	0.48
B', E'	$F_{4,4}$	2.49	1.27	1.95
(0°)	p	0.20	0.41	0.27
C', F'	$F_{4,4}$	2.17	2.08	4.51
(−15°)	p	0.24	0.25	0.09
Pooled	$F_{12,12}$	1.28	1.37	1.76
	p	0.34	0.30	0.17

Table 2.43: Differences in the magnitudes of the indication errors between session 1 in VKSIM.I and VKSIM.III

|Session 1 in VKSIM.I| − |VKSIM.III|

Target	Result	Direction of head tilts A(90^o)	B(0^o)	C(-90^o)	Pooled
A', D' (15^o)	Diff.	1.62^o	-1.81^o	5.74^o	1.85^o
	df	4	4	4	12
	Variance	4.13	7.50	4.62	5.42
	t	1.78	1.48	5.97**	2.87*
B', E' (0^o)	Diff.	-0.88^o	-2.84^o	5.95^o	0.74^o
	df	4	4	4	12
	Variance	8.26	11.88	20.89	13.68
	t	0.68	1.84	2.91*	0.72
C', F' (-15^o)	Diff.	-0.85^o	-0.97^o	3.15^o	0.44^o
	df	4	4	4	12
	Variance	8.69	2.77	13.80	8.42
	t	0.65	1.30	1.90	0.55
Pooled	Diff.	-0.04^o	-1.87^o	4.95^o	1.01^o
	df	12	12	12	36
	Variance	7.03	7.38	13.10	9.17
	t	0.05	2.48*	4.93**	2.03*

Table 2.44: Differences in the magnitudes of the indication errors between session 2 in VKSIM.I and VKSIM.III

|Session 2 in VKSIM.I| − |VKSIM.III|

Target	Result	Direction of head tilts A(90^o)	B(0^o)	C(-90^o)	Pooled
A', D' (15^o)	Diff.	3.15^o	3.01^o	4.70^o	3.62^o
	df	4	4	4	12
	Variance	6.45	9.33	4.52	6.77
	t	2.77	2.20	4.94**	5.02**
B', E' (0^o)	Diff.	2.52^o	0.51^o	7.55^o	3.52^o
	df	4	4	4	12
	Variance	17.75	0.72	23.01	13.83
	t	1.34	1.34	3.52*	3.41**
C', F' (-15^o)	Diff.	-1.20^o	4.31^o	7.60^o	3.57^o
	df	4	4	4	12
	Variance	32.57	5.12	7.69	15.13
	t	0.47	4.26**	6.13**	3.31**
Pooled	Diff.	1.49^o	2.61^o	6.62^o	3.57^o
	df	12	12	12	36
	Variance	18.92	5.06	11.74	11.91
	t	1.24	4.18**	6.97**	6.29**

showed the same pattern of indication as in VKSIM.I, i.e. the indications were biased in the direction opposite to the tilt of the head (also see figure 2.38). Comparing the results in table 2.20 and 2.39, we see that the variances and the indication errors in the 90^o tilted positions (column A and C) are smaller; but those in the upright position (column B) are larger in VKSIM.III than in VKSIM.I. Table 2.42 contains the F-test results between variances in VKSIM.III. The subject did not show any increase of variance when the head was tilted (table 2.42) as he did in VKSIM.I (table 2.25).

Since the subject showed the same effect as a result of the head tilt in both experiments, only the magnitudes of the corresponding indication errors are compared. Table 2.43 and 2.44 indicates that the subject showed remarkable differences between these two experiments. When the head was tilted toward the non-dominant hand (column C), the differences were greater and most of them were statistically significant. When the head was tilted toward the dominant hand (column A), the differences were not significant. The control (head upright position—column B) also had notable differences. When pooled, they were also significant ($p < 0.05$ between session 1 in VKSIM.I and III; $p < 0.001$ between session 2 in VKSIM.I and III), as was the grand difference ($p < 0.05$ between session 1 in VKSIM.I and III and $p < 0.001$ between session 2 in VKSIM.I and III).

2.5.3 Discussion

The significant overall differences between the indication errors in the case of both D and B, and F and B, rule out the straightforward explanation about the

VKSIM.II indication differences between the horizontal and the upright body positions proposed in the previous section. Thus we should inquire further into the alternative explanation also mentioned in the previous section: that the indication difference was caused by the body positions, i.e. the body position relative to the gravity vector. This means that it is the 90^o directional change of gravity relative to the body that caused the VKSIM.II indication difference, despite the fact that the 180^o (from left side to right side) change did not. This suggests that the subjects may use a different reference strategy for orientation when the whole body is in a horizontal position.

As will be discussed further in the next chapter, we believe that non-visual orientation is actually a collection of associations between a subject's ***internal perceptual states*** and the external directions that are verified by visual information. For a normal subject, the association between the perceptual state of the "upright body posture" and the "vertical" is probably the most important one. Notice that the "upright body posture" is the posture the subject perceives as upright, and the "vertical" is the direction the subject perceives as vertical. They are referred to as the ***subjective posture upright*** and the ***subjective control vertical***. They are also called the ***primary body position*** and the z-axis of the subject's ***control subjective reference frame***. Therefore, they are not necessarily the same as the true upright or vertical. But they are believed to be close enough for general daily functioning. This perceptual state is referred to as the ***primary reference perceptual state***. I believe that a subject's perception of the body's position in space is measured from this "reference state". For example, when a subject's body is not in the upright position, the perception of the body position is arrived at by comparing the ***instantaneous perceptual state*** with the memory of the reference state. The orientation scheme using this "primary reference perceptual state" is referred to as the ***primary scheme***.

Since the horizontal body position is the second most common position in daily life, the subject may have a different reference perceptual state in the horizontal position. Every time a person lies down he has to reorient himself according to the altered visual world. Thus a ***secondary reference (perceptual) state*** is established in association with the gravitational horizontal. When a subject's body is near the horizontal, the perception of body position may be based on this "secondary reference perceptual state". In turn, his orientation scheme is called the ***secondary scheme***. A normal person may spend approximately equal amounts of time lying on the left or on the right, as was the case for this subject in this experiment. Thus the "secondary scheme" is approximately the same when the body tilts left and right. This means that the subject's orientations in both left and right positions are practically the same, as reflected by the equivalent indications by the subject in those positions.

The utilization of this "secondary scheme" may begin with the subject's belief that his body is near the horizontal position. If the subject is very confident about his body's position being in the horizontal or the vertical, he is expected to use only one reference state consistently. Therefore, under the circumstances of knowing that his body is in the horizontal position, this secondary reference state is utilized spontaneously and consistently. In some cases, a subject may feel equivocal about which scheme he should use. He may feel bound with one scheme at one moment[5] and the other at another moment. Normally, these two schemes do not yield consistent results. Consequently, his perception of the body position would vary from moment to moment. It is not well understood why this is so, but it does happen. However, some people can exert a little control over these perceptions by mental concentration. Notice that only one scheme is in operation at any one time, i.e., the subject has only one orientation at a time. If the subject has to report or indicate his perceptions, his reports or indications are expected to be influenced by both of the momentary perceptions in this case. How the influence is reflected is very much subject dependent. One subject may report or indicate the perception only based on his "instantaneous perception". Thus his reports or indications are expected to be "time-variant". Another subject might be inclined to exert more mental control over his reference scheme to produce more consistent reports or indications. A third subject might be inclined to use a neutral technique to "take care of" both orientations suggested by both schemes. Instead of reflecting only one of the perceptions, his reports or indications are somewhere in between the two suggestions. Statistically, he might give the same mean report or mean indication as the first subject. But his reports or indications would be more consistent.

The well-known *rod and frame* tests are also effected by the choice of reference

[5]*Bound with* describes the momentary sensation when a subject feels that only the orientation suggested by one scheme is present.

state. As we all learn, visual information is the most reliable in everyday orientation. We have no doubt that the buildings, trees, and pedestrians we see are vertical, and that floors, water surfaces, and beds are horizontal. Visual information dominates the determination of the reference perceptual states. In the *rod and frame* tests, an upright subject provided with a visual scene is asked to indicate the vertical. In most cases, the visual scene offers conflicting cues of direction. Therefore, the visual and non-visual cues suggest inconsistent orientations. If the subject has complete confidence about his non-visual perception, he could completely disregard the visual scene and orient himself based on his primary or secondary reference state as he normally does.

If the subject is convinced about the reality of a visual scene, he would choose the orientation suggested by the visual scene. Instead of feeling that his body is in the upright, he would believe that his body is tilted. The amount of tilt equals the angle between his body and the "upright" suggested by the visual scene. The direction of the suggested tilt is opposite to the tilt of the visual scene from the true upright. Then he would associate his current perceptual state (which would be the primary reference state) with his perception of the body's position. This association establishes a *third reference perceptual state*. If his body is truly tilted, he would then calculate the body tilt by comparing his instantaneous perceptual state and the "third reference perceptual state". But the "rod and frame" test is only concerned with the indication of the vertical, not the perception of the body's position.

In most cases, a subject does not have complete confidence in either orientation. As discussed earlier, with the two orientation schemes, the subject may feel bound with one suggestion at one moment, and the other at another. Then the indication of the vertical is expected to be subject dependent and fall into three categories as discussed earlier. Most subjects are expected to be in the first or the third categories. They show the influences of the visual and non-visual cues. Furthermore, the influence of a visual scene depends largely on the "relative strength" of the visual scene. The "relative strength" means how realistic a visual scene feels to the subject. For example, a scene composed of a plain visual line \ or / has less strength than a scene composed of pictures of standing houses, trees, and people. A tilted room in which a subject sits might have the greatest strength.

From the discussion above, we see that establishment of a "reference perceptual state", and comparison between an instantaneous perceptual state and the reference perceptual state, are believed to be the keys to a subject's orientation. In the following chapter, we will try to postulate how these should be done. Then we will use these concepts to postulate a subject's information processes in the KSV, VSV, VST and VKSIM experiments.

Chapter 3

Modeling and General Discussion

Human orientation with respect to the vertical has been an active field of research for more than a century. Many exciting experimental results and theories have been put forward. Frequently the theories were based on the results of only one, or one series of, experiments and therefore only concentrated on one aspect of the vast issue. Sometimes theories proposed by different investigators were contradictory to one another. There is therefore a need for an integrated theory or model. This model should be able to resolve the contradictions between the VSV and KSV indications, between VSV indications and the VST indications [2], and to interconnect those experiments with the "rod and frame" test, tilt normalization (tilt adaptation), human orientation adaptation, etc.. This chapter will discuss these issues in theory based on known facts and scientific imaginations.

3.1 Perception of body status and construction of SRF

For a control engineer or a physiologist, it is very tempting to model the human verticality perception/indication process solely within subject's body frames. It is straightforward to think that, in the VSV experiment, a subject would set the visual line indicator on a tilt from his body in the direction opposite, but by the same amount as, the estimated tilt of his body from the vertical; and that in the VKSIM tests, a subject would set the *Rod Indicator* tilted from his body in the same direction and by the same amount as, the perceived tilt of the visual line from his body. But the situation is more complicated and subtle than that.

The subjects in the previous experiments were asked what reference they used during the tests. Based on their reports and my own experience, it seemed that a subject was able to visualize the vertical and horizontal directions in a plane parallel to his frontal plane. Both the visual line and the rod were perceived as inclined relative to the visualized vertical or horizontal. Therefore, the indications were done in those visualized space coordinates. These space coordinates will be referred to as the *Subjective Reference Frame* (*SRF*). Stated in more general terms, a ***Subjective Reference Frame*** (*SRF*) denotes the pure subjective or imaginary reference frame that a human subject creates when he orients himself in the external world. Since humans live in a four dimensional space, this SRF should also be four dimensional—including one temporal and three geometrical dimensions. What we are concerned about here is the two geometrical dimensions in the roll plane: up-down and left-right.

In normal situations, a subject is always in a position near the upright or what he believes is the upright. For convenience, the subject may simply regard his longitudinal axis as the "vertical". Normally, this assumption is consistent with visual cues. This body position or the perceived "vertical" will be called the ***primary body position***, ***primary subjective vertical***, or ***control vertical*** (which is also the z-axis of the control SRF). As long as the subject believes that he is in the upright, he orients himself in this way with confidence.

In order to know that he is in the upright, he must memorize the non-visual sensory information pattern when he is in the upright. This pattern is called the ***primary perceptual state*** or ***control state***. If an instantaneous sensory information pattern or perceptual state matches the "primary perceptual state", the subject would perceive himself as being in the primary body position, i.e. "upright". This means that, for a normal subject in an upright posture and in a normal environment, the SRF axes are expected to be aligned with the body axes and also the external frame. For instance, one normally associates standing postures, walls of buildings, and trees with the upright; the surfaces of water, floors, and beds with the horizontal.

These associations are expected to be developed by various sensory functions such as vision, hearing, gravity sensing, and touching, etc. Vision probably plays the most important role since it usually offers the most accurate and explicit information about the external world. Therefore, in everyday orientation, visual cues are dominant and non-visual cues only play complimentary roles. It is also because of the consistency between these two sets of cues that we do not distinguish their different functions. Their functional differences are seen better when they offer inconsistent orientations such as in weightlessness or in the case of loss of a major kinesthetic sensory organ. A subject in these cases would eventually adapt in the visual world by changing the scheme for analysis of non-visual cues. This suggests that the visual cues are expected to offer information about the external world, i.e., ORF, and the non-visual cues are used to establish the SRF. In normal situations, SRF is verified by visual cues. If the verification succeeds, the SRF construction scheme gains a higher confidence level and one can orient oneself well in everyday activities. If the verification fails, one may experience disorientation. Furthermore, the SRF construction scheme may be subject to an adaptation process. In certain circumstances, a subject can be trained to ignore conflicting non-visual cues. That fighter pilots are always advised to utilize instruments (visual cues), rather than subjective sensations when flying, is an example of such training.

When a subject is not in the upright position his sensory pattern changes, which informs the subject that his body has moved away from the primary position. Based on "experiences", he would know with a certain confidence the direction of the change (see figure 3.1). Thus he can relocate where the vertical would be with the same confidence. This relocation process is also called "SRF construction". The relocated vertical is then verified by visual cues. If the verification is successful, the scheme would be confirmed once more and gain a higher confidence level. If the verification is not made, the CNS would then check which information is most

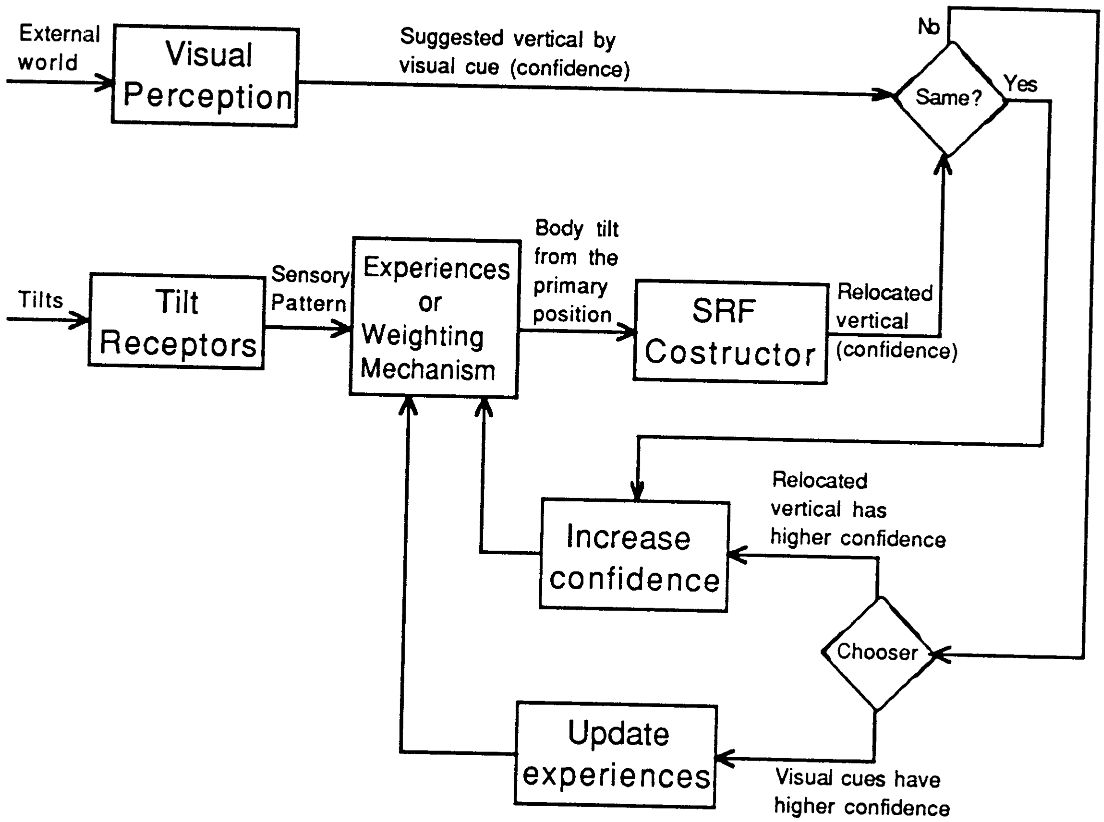


Figure 3.1: Illustration of orientation scheme.

believable. If the relocated vertical has higher confidence level it is regarded as the vertical, and the visual object would be regarded as an object in the newly constructed SRF space. If the visual cue has higher confidence level, the CNS would then take the suggestion of the visual cue and update the SRF construction scheme accordingly.

In some cases, the visual cue and the non-visual cue have approximately equal confidence levels. In these cases, the subject's orientation might change momentarily (as mentioned in the discussion of VKSIM.III section in the last chapter), and if the subject is asked to indicate or report the vertical direction, he would then show influences of both visual and non-visual cues (see section 2.5.3 for details). When a subject's orientation mechanism is disturbed, he will experience disorientation.

In this thesis, any of the following three situations are considered to be disorientation: (1) dizziness and/or vertigo—normally caused by malfunction of sensory organs, (2) loss of the sense of direction—may be accompanied by minor dizziness, and (3) confidence in a sense of direction which is actually wrong, and which affects daily activities.

A disturbance is therefore characterized as a large misalignment between a subject's SRF and ORF, such that the subject experiences disorientation. Small daily fluctuations of the alignments are not considered to be disturbances if disorientation has not occurred. A disturbance can be caused by a change of either the SRF, ORF, or both.

The degree of the disorientation is of course dependent on how serious the disturbance is. In the case of loss of a major sensory organ, the disturbance can be enormous and may immediately and totally disrupt the victim's entire orientation. The subject has to establish a new SRF construction scheme to align the new SRF with the ORF. This process is called *perceptual adaptation*. It is believed to be a dynamic process. Therefore, after the new SRF is established and reaches a steady state, the subject can recover his orientation. In the case of a small disturbance, such as that imposed by a head tilt, the disorientation may be so small and the associated recovery so fast that the subject may not even notice it. One simple example would be the minor disorientation one experiences when facing a familiar street with one's head tilted and eyes closed and suddenly opens the eyes. In this case, reorientation and recognition of the surroundings is relatively quick.

In the case of major sensory organ loss, the construction of a new SRF will take a longer period of time and may have reduced functional accuracy and dynamic range. In the second example, the reconstruction of a SRF is relatively trivial, especially in the presence of the explicitly visual world. The subject can simply adopt the *ORF* as the *SRF*. This is fulfilled by establishing a new "perceptual state" as discussed on page 86 in the context of the "rod and frame" test. But in the absence of the visual world, the construction will be much more complex. In that case, the construction of the new frame relies totally upon non-visual information: vestibular inputs, kinesthetic cues, knowledge of one's body status or of the external world, etc.

In our experiments, the visual cues are either cut off (in KSV), or very weak (in VKSIMs). In addition, the inspection time was limited to within 20 seconds in VKSIM experiments. Therefore, we can ignore the influence of the visual cues on the perception of the vertical (probably within 1^o). In the following paragraphs, I will discuss in detail how the relocation of the vertical is achieved based solely on non-visual cues.

Before going into a formal discussion, a few key terms must be defined or clarified. A *Torso tilt* represents the angle between the mid-torso line and the gravitational vertical. A *Head tilt* denotes the angle between the median line of the head and the mid-torso line. An *Overall tilt* is the sum of the previous two, i.e. the angle between the head and the gravitational vertical. It is also referred to as an *Otolith tilt*. A *Whole body tilt* means a tilt of the entire body as a whole (without any bending or twisting of any individual part). A *body tilt* is a general term, which can mean a torso tilt, head tilt, whole body tilt or a combination of these. All the tilts are denoted by positive angles if the tilts are toward the DH side, and by negative angles otherwise. In the right-hand coordinate system we use (see figure 3.2) the DH side always corresponds to the negative side of the y-axis. In other words, the DH is normalized as the right hand in this coordinate system. Figure 3.3 illustrates various body coordinates in a subject's frontal plane.

The tilt(s) of the body (a tilt of the head, torso, whole body, or a combination of them) stimulate various sensory organs such as stretch sensors, joint receptors in the neck and torso muscles, pressure sensors in the buttock muscles, and hair cells in the otolith organs. In response to these stimuli, the firing rates in the associated

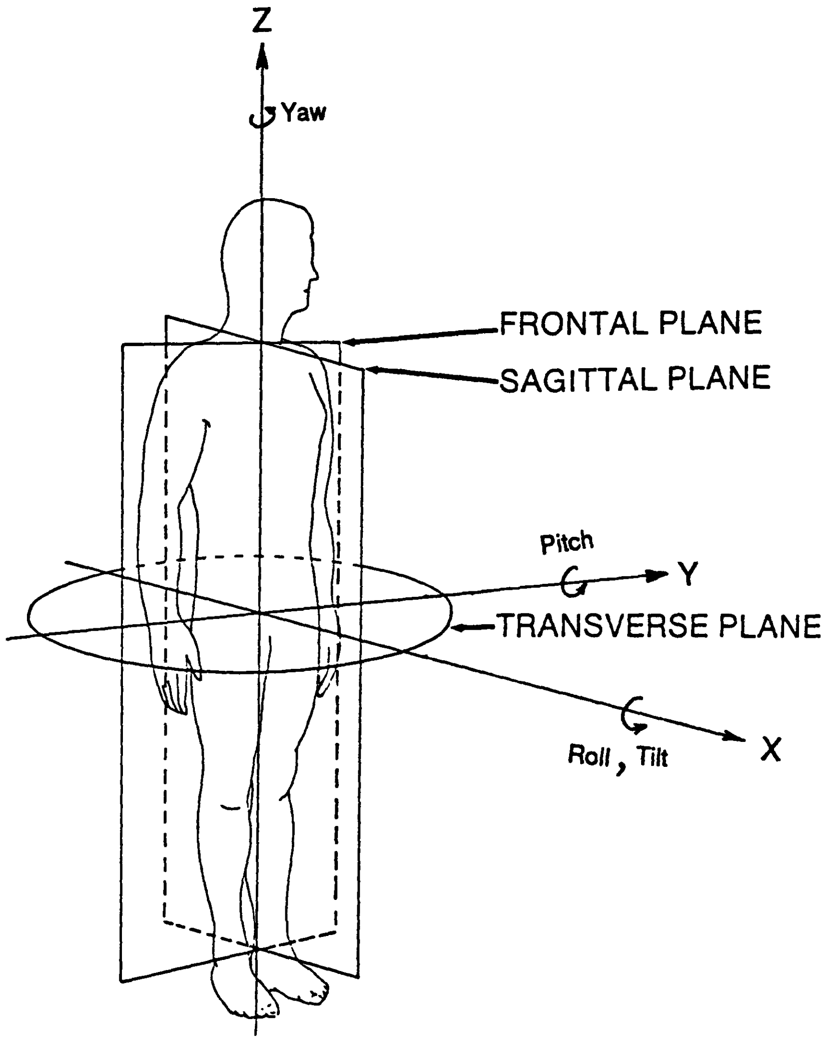
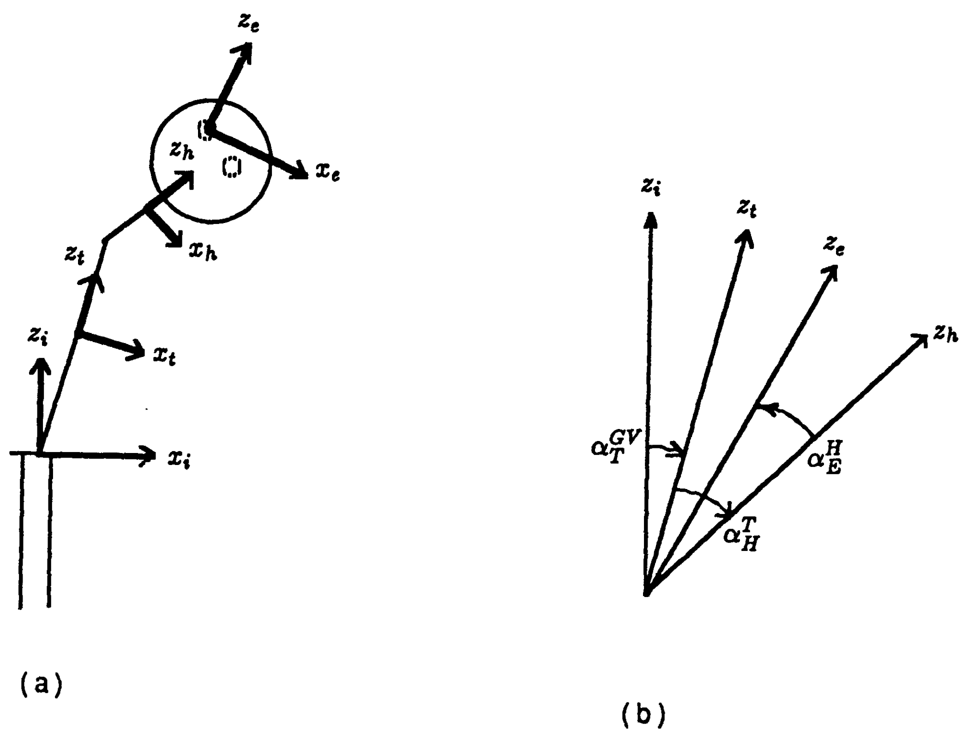


Figure 3.2: Illustration of the coordinate system used



Viewed from behind the subject

Figure 3.3: Geometrical relations among various frames
(a) illustrated in two dimensions; (b) illustrated in one polar dimension.
x_i, z_i: x and z axes of inertia coordinates; x_t, z_t: x and z axes of torso coordinates; x_h, z_h: x and z axes of head coordinates; x_e, z_e: x and z axes of eye coordinates;

afferent nerves will increase or decrease. For the purpose of modeling we presume that a *Weighting Mechanism* in The CNS integrates this information to produce the best estimates of the body tilts (figure 3.4; the meaning of all the symbols are listed in "List of Symbols" in the front matters of this thesis).

These estimates are perceptions of the various tilts, and, being psychological entities, cannot be directly measured. So far, probably the best ways to evaluate them are subjective magnitude estimation and subjective indication. The latter is the technique we have used for measuring the perception of the vertical. The former technique may not have been used for evaluation of the perception of the vertical, but is well developed and documented elsewhere [42,43,44,45].

Now let us discuss each of the elements in figure 3.4. Among non-visual information, the otolith input is probably the most profound since the otolith is a gravity sensor and gravity is the most pervasive and constant force in the earth's environment. The stimuli to the otolith, i.e. the effective forces, is a sine function of the angle of the head tilt from the vertical. For small overall tilts, the changes of the firing rates in the associated afferents are approximately linear to the tilts; but for large tilts, the otolithic inputs to the CNS saturate (see otolith element in figure 3.5). Hence, the CNS is physiologically under-informed about large overall tilts by the otolith.

Body tilts also stimulate sensory organs such as golgi tendon organs, muscle spindles, joint receptors, and pressure sensors. They also play roles in orientation. In general, when a mechanical stimulus is in the daily dynamic range, a mechani-

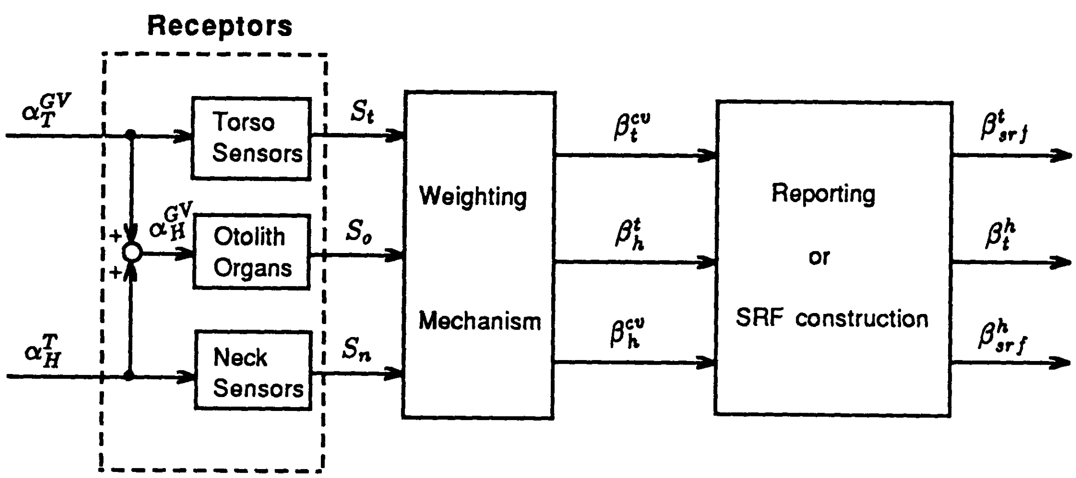


Figure 3.4: Control diagram of the perception process of body status

cal sensory system responds linearly to the stimulus. But when the stimulus goes far beyond the daily dynamic range, the sensory system frequently becomes less responsive. This is known as saturation, and has been found in many sensory end organs such as muscle spindles [21] and golgi tendon organs [14], etc.. Therefore, it is reasonable to assume that the responses of the kinesthetic sensory systems to body tilts are linear for small tilts, and saturated for large ones (figure 3.5). Furthermore, we ignore the change of the pressure distribution on the buttocks and the stimulation to the stretch or joint receptors in the torso muscles caused by pure head tilts. Therefore, it is assumed that a head tilt (relative to the torso) only stimulates the neck sensors and the otolith organs.

Notice that the slopes of the linear portions of the transformation curves in the three blocks are unimportant and unspecified since they are totally dependent upon the units used. The important thing is the shapes, i.e. the linearity for small tilts and the saturation for larger tilts.

The outputs of these three receptor elements are all physiological signals. They enter the physio-psychological converting element called the Weighting Mechanism or Estimator and produce the various perceptions of the body tilts (see figure 3.4). The algorithm of this Weighting Mechanism is unknown, but we have to make the best assumptions that we can in order to simulate the process.

It is straightforward to assume that the CNS attributes the signals from the various torso sensors S_t to a tilt of the torso, and the signals from the neck-sensors (S_n) to a tilt of the head relative to the torso. But how does the CNS interpret the

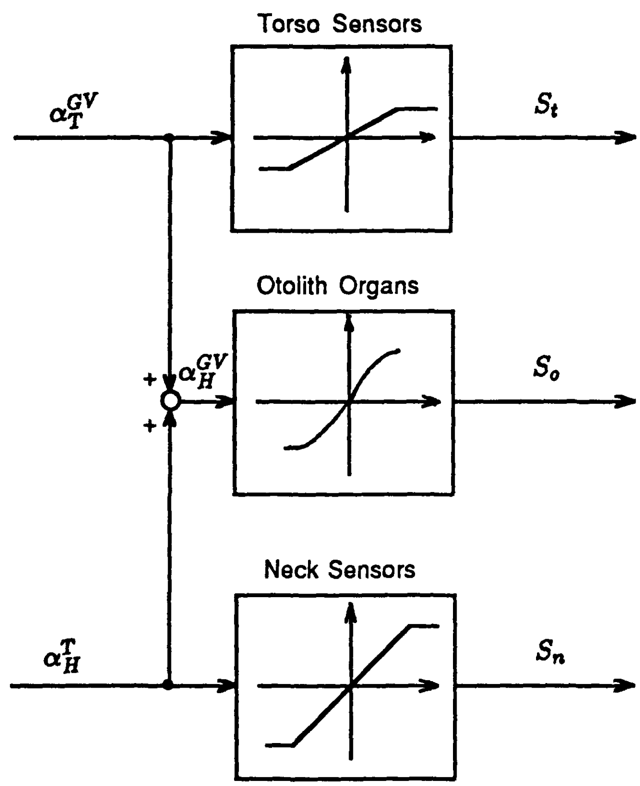


Figure 3.5: Illustration of the hypothesized characteristics of the Receptors.

signals from the otoliths (S_o): as a tilt of the head, the torso, or both? When the head is in alignment with the torso, the CNS must interpret the signals from the otolith (S_o) as a tilt of the torso, i.e., the entire body. When the head is tilted and the torso is maintained upright, the CNS must interpret the otolith signals S_o as a tilt of the head. When both the torso and the head (relative to the torso) are tilted, the CNS should be able to split the otolith inputs into two parts based on the inputs from the torso and neck-sensors. One part contributes to the perception of the tilt of the torso and the other to the perception of the tilt of the head (relative to the torso). This is expected to be done in the element of Weighting Mechanism. Let S_o^t and S_o^h represent the portion of S_o contributing to the perception of the tilts of the torso and head (relative to the torso) respectively. Then the hypothesized scheme of the split is

$$S_o^t = \frac{S_t}{S_t + S_n} S_o$$
$$S_o^h = \frac{S_n}{S_t + S_n} S_o$$

Then S_o^t and S_o^h together with S_t and S_n will be further weighted in the Weighting Mechanism to produce the perceptions of the torso and head tilts. For generality, we assume that S_t and S_o^t have unequal weights, and so do S_n and S_o^h. Thus the perceptions are:

$$\beta_t^{cv} = W_t^t S_t + W_o^t S_o^t$$

$$\beta_h^t = W_n^h S_n + W_o^h S_o^h$$

where β_t^{cv} is the perceived tilt of the torso relative to the *control vertical (cv)*, i.e., the ***primary body position*** (see page 90). β_h^t is the perceived tilt of the head relative to the torso, W_t^t, W_n^n,W_o^t and W_o^h are the weighting coefficients. The subscripts indicate the contributing receptors, and the superscripts indicate the contributed perceptions.

Another output of the Weighting Mechanism element is the perceived tilt of the head relative to the control vertical β_h^{cv}. If the perceptions are euclidean metrics, then β_h^{cv} is the sum of β_h^t and β_t^{cv}. But for conservative reasons, we do not rely on this assumption.

It has been reported that adaptation of the neck and torso sensory systems influence the perception of the overall head tilt [50,52,53]. This suggests that the signals from the neck and torso sensors contribute to the perception of the overall head tilt. Expressed in a mathematical formula, we have

$$\beta_h^{cv} = W_t^o S_t + W_n^o S_n + W_o^o S_o$$

where W_t^o, W_n^o and W_o^o are weighting coeffecients. These coefficients are really the key connections between physiological signals and psychological perceptions. Their values, although unknown, are assumed to be adaptable. It is these adaptable coefficients that make the adaptability of human orientation possible.

Although we have developed a model for the Weighting Mechanism, we are unable to indentify the exact values of these internal parameters. In order to simulate the input-output relationships, we must assign those parameters reasonable values based on our experiences and assumptions.

First, let us start with a small experiment. Seat yourself in a chair in front of a mirror with your eyes closed. Then tilt both your torso and head to the same side, with your head tilted a little further than your torso. Now try to visualize the angle of the tilt of your torso from the vertical, then the angle of your head from your torso. Only try to visualize and feel the tilts. Do not try to give any quantitative answer, because we do not want to deal with "reporting". When you open your eyes, you will probably find that you over-perceived the tilt of your torso and under-perceived the tilt of your head from your torso. Nagel (see [15] pp194) also reported that, when he lay on his side, he felt as if his body was tilted more than it was. Furthermore, McFarland, *et al.* [22] and Bauermeister [2] found that people tend to over-estimate the tilt of the body from the vertical. In their experiment, subjects were asked to set a luminous rod parallel to their mid-torso line when their body's were tilted. The subjects over-indicated the body tilt. We will see in the following sections that this over-indication is possible only if the subjects over-perceived or over-estimated the tilt of the body. Therefore, the Receptor and the Weighting Mechanism elements together will have input-output characteristics as illustrated in figure 3.6. Notice that in these diagrams, the saturation properties were assumed to persist from the physical-physiological level. Since large tilts are novel body positions for a normal human, the associated responses, and thus the inputs to the Weighting Mechanism, are also rarely encountered. Therefore, the Weighting Mechanism is unable to compensate for saturations that took place at the lower levels. The saturations manifest themselves as under-perceptions of the appropriate tilts.

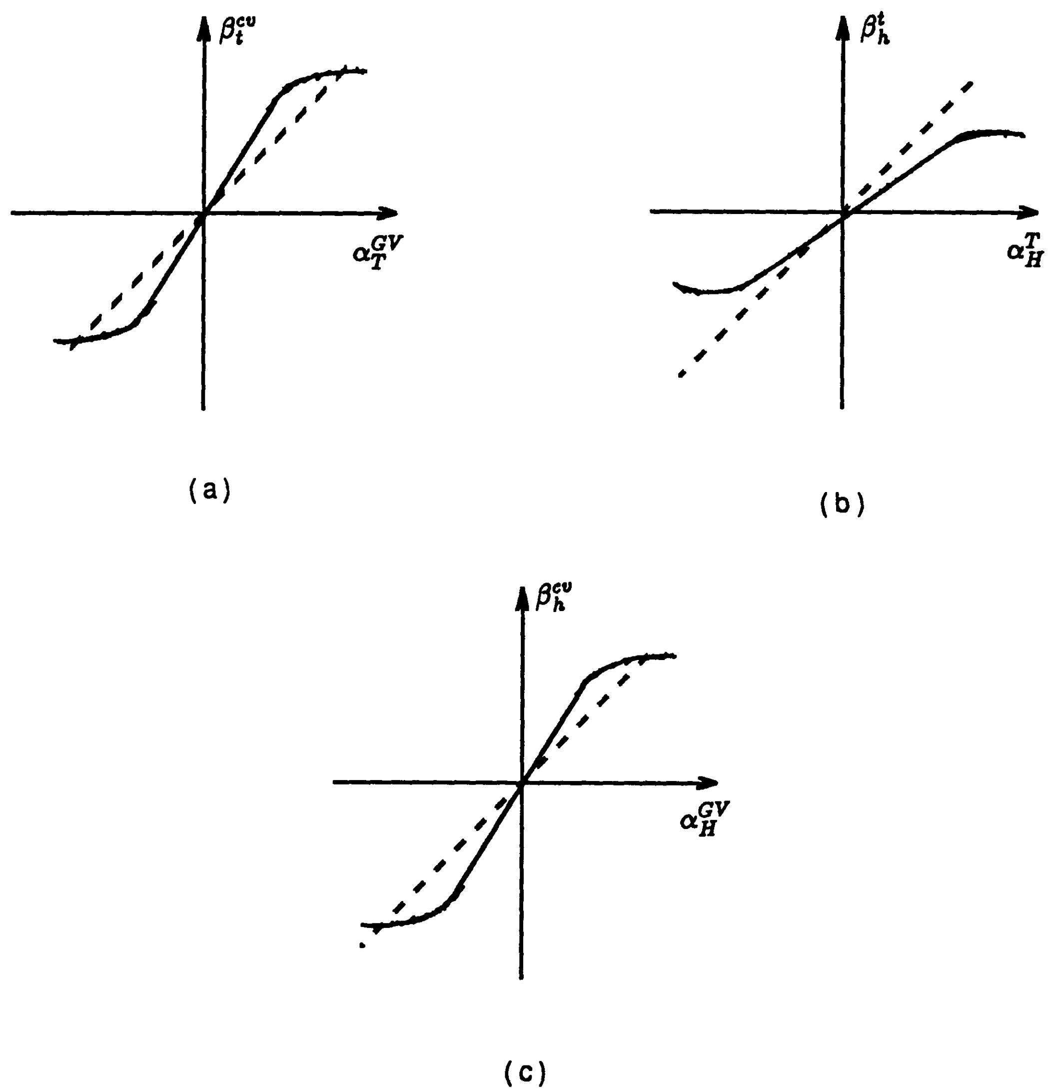


Figure 3.6: The input-output relationships between the tilts and their perceptions

The broken lines have unity slopes, representing unit gains of perceptions. The meanings of the symbols are listed in "List of Symbols" on page 7: (a) perception of the torso tilt from the control vertical as a function of the physical tilt of the torso; (b) perception of the head tilt from the torso as a function of the physical head tilt; (c) perception of the overall head tilt as a function of the physical overall head tilt.

To be measured, these perceptions have to be reported or indicated after a SRF is established. As discussed at the very beginning of this chapter, the subjects can visualize the vertical in front of them and indicate it. The visualization is based on the various perceptions such as β_t^{cv}, β_h^t or β_h^{cv}. This visualization is somewhat similar to the well known " magnitude production" technique used in psychophysical research, even though the former does not produce any physical quantity. To the subjects themselves, the visualizations are as substantial as the physical productions. Therefore, the visualization might be expected to have the characteristics of "central bias" and "conservatism". Central bias represents the phenomenon in which humans over-estimate the input when it is below its central value, and underestimate it when it is beyond its central value (see "central bias" element in figure 3.7). Conservatism means that the human subjects have the tendency of unwillingness to go extremes in their estimation when the input reaches its boundaries (see "conservatism" element in figure 3.7). Conservatism is sometimes called "regression" or "central tendency" [47]. In some sense, the "central tendency" includes both the conservatism and central bias effects. But for clarity, these two effects are seperated in this thesis.

It is believed that a subject can always visualize the vertical. It seems as though the subject always has an implicit Subjective Reference Frame (SRF) within him. The visualization mechanism will be referred to as *SRF construction* and is represented by a *SRF constructor* in figure 3.7. Notice that the negative unit gain is required by the sign convention we use (see figure 3.2 and 3.3). The inputs β_t^{cv}, β_h^t and β_h^{cv} are measured from the control vertical to the torso, from the torso to the head, and from the control vertical to the head. The outputs β^t_{srf}, β^h_t and β^h_{srf} are measured in exactly the opposite direction: from the SRF to the torso, from the torso to the head, and from the SRF to the head. For example, if β^{cv}_t, β^t_h and β^{cv}_h are clockwise, then β^t_{srf}, β^h_t and β^h_{srf} are counterclockwise, and vice versa.

When the outputs from the Weighting Mechanism enter this constructor, the final outputs as functions of physical tilts are as illustrated in figure 3.8.

Notice that because of the non-euclidean phenomenum, the three constructed psychological quantities may not be consistent, i.e., the mathematic relationship

$$\beta^h_{srf} = \beta^t_{srf} + \beta^h_t$$

is not guaranteed.

The concept of the SRF construction is the key idea in this model. Only after the subject constructs the SRF can he indicate the vertical, the torso position, etc..

For convenience, the entire process of vertical perception and SRF construction will be referred to as a *SRFer*, which includes the Receptors, Weighting Mechanism and SRF Construction elements.

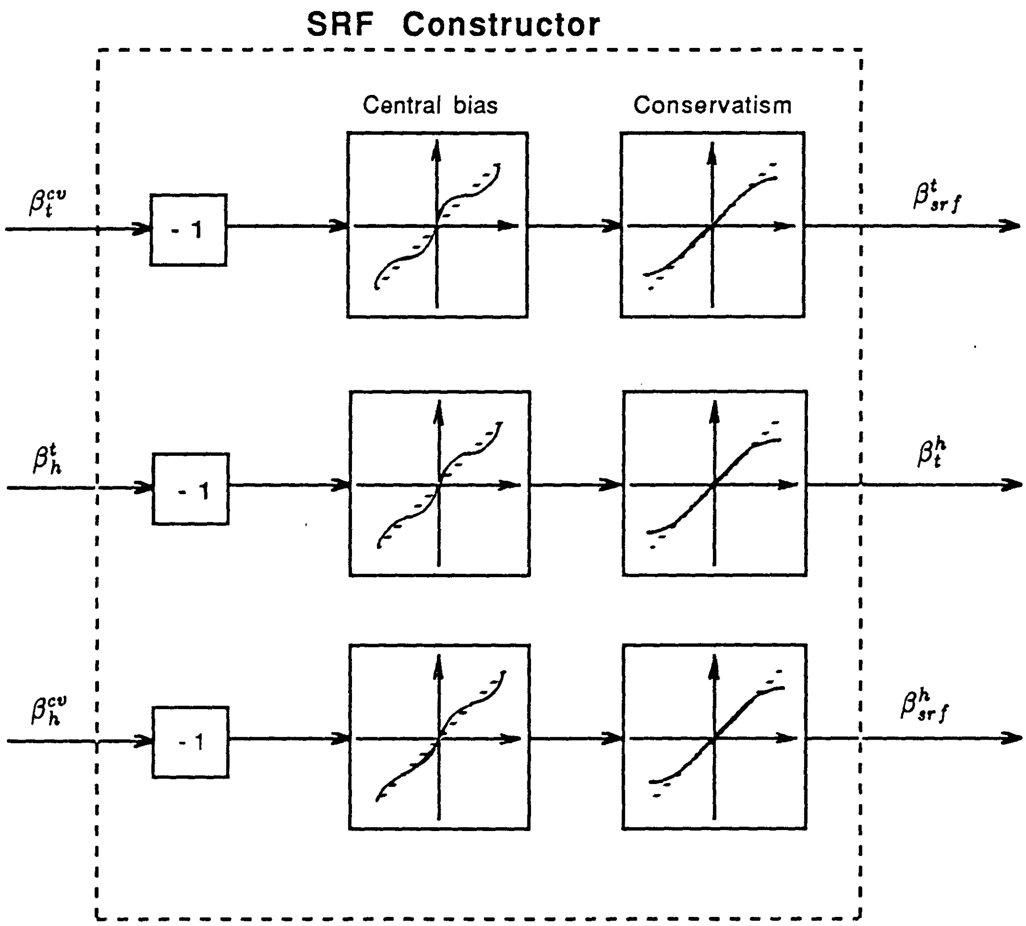


Figure 3.7: Illustration of SRF construction.

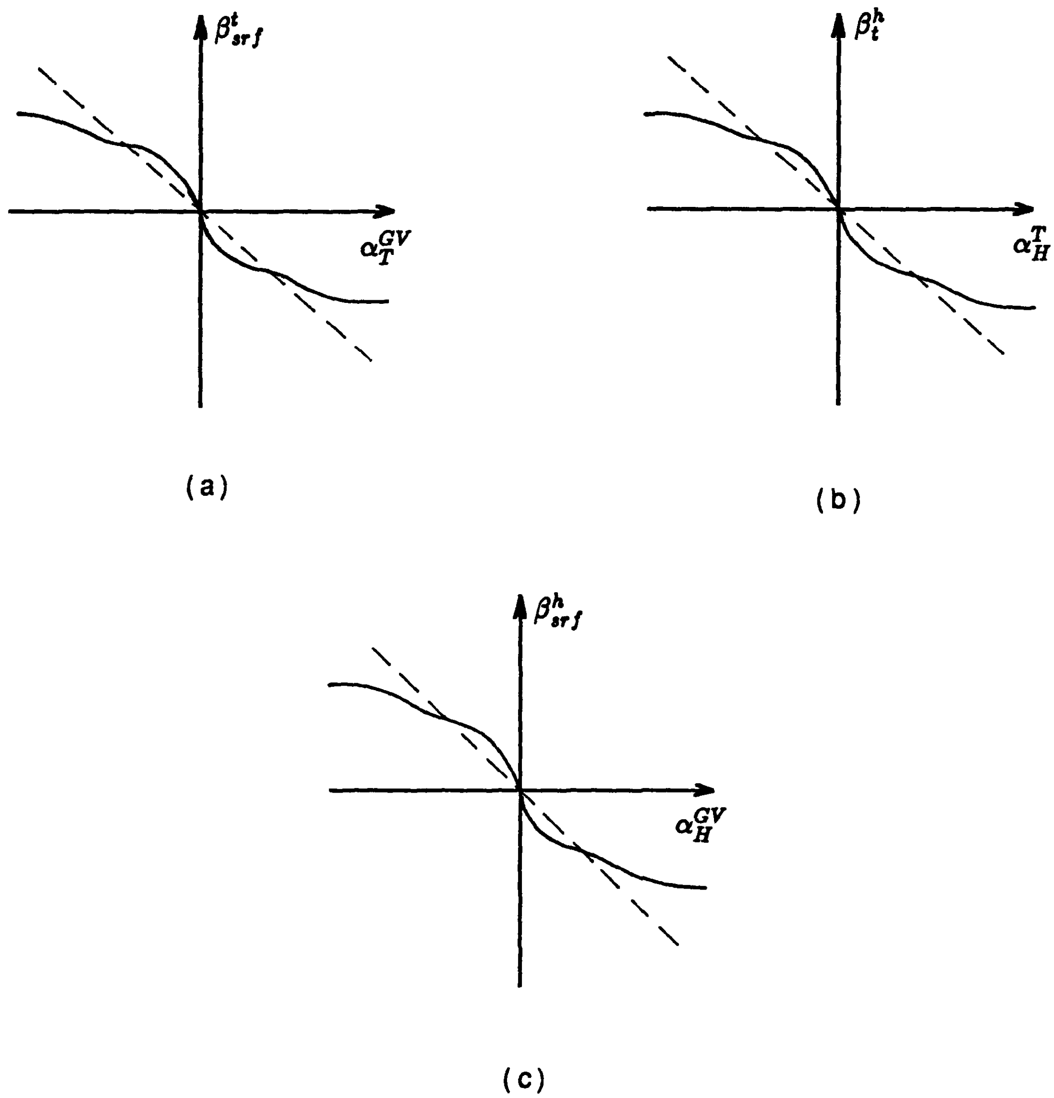


Figure 3.8: Final outputs from the verticality perception model

Meanings of the symbols are listed in "List of Symbols" on page 7. Broken lines represent unity (-1) reconstructions. (a) constructed SRF z-axis (or subjective vertical) relative to the subjective torso position as a function of the physical torso tilt; (b) constructed of subjective torso position relative to subjective head as a function of the physical head tilt; (c) constructed SRF z-axis relative to the subjective head as a function of the physical overall head tilt.

3.2 VSV indication process

Figure 3.9 illustrates the control flow diagram of the Visual Subjective Vertical (VSV) indication process. A subject receives information about the tilts of his head and torso, and the visual indicator's position relative to the vertical meridians of his retinae. The task is to set the visual indicator in an inclination so that the perceived position of it in the SRF coordinates or space is aligned with the z-axis. When they are not aligned, the CNS sends a signal to the subject to adjust (by verbal instruction) the visual line indicator. This process continues until alignment is reached. The final position of the visual line is the subject's indication of the vertical, and is referred to as VSV (Visual Subjective Vertical) indication.

It has been well-known to psychophysicists that perceptual continua fall into two classes. Class I, for which discrimination appears to be based on an additive mechanism by which excitation is added to excitation at the physiological level is labeled *prothetic*. In these kind of continua the perceptions are normally power functions of the inputs, such as those we discussed in the previous section. Class II is called *metathetic* for which discrimination behaves as though based on a substitutive mechanism at the physiological level. Pitch and visual inclination belong to this class, since these different stimuli excite different groups of cells in the sensory organs. Joint angle is also metathetic since joint receptors fire in a particular pattern at a particular joint position. Normally, a metathetic continuum shows linear input-output relations [46].

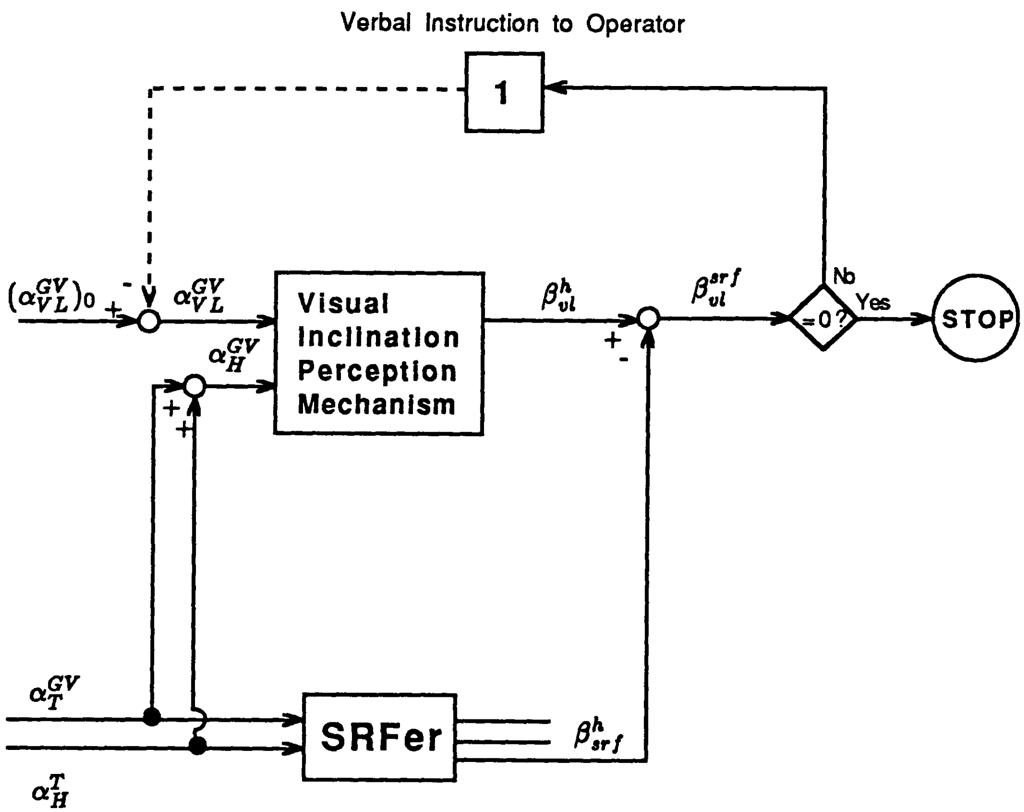


Figure 3.9: Control diagram of VSV indication process

The broken line in the feedback loop means that the subject himself does not have physical contact with the visual line indicator.

For a normal erect human subject, the retina images of a line in a plane parallel to the subject's frontal plane fall approximately on a certain pair of meridians in the retinae and only the group of cells on these meridians are excited. The perceived inclination of the visual line is based on which retina meridians are stimulated, i.e., the visual inclination is a *metathetic* continuum. Therefore, a linear relationship between the physical inclination and its perception is expected. This was also suggested by Volkman's unpublished results cited by Stevens [46]. This relation is expressed by an unit gain between α_{VL}^{E} and β_{vl}^{e} in figure 3.10. Here we group the two physical-physiological and physio-psychological processes together as one physical-psychological process.

The link between a physical inclination and a pair of retinal meridians is well established during daily life. Thus the linear relationship between a pair of meridians and the perception of an inclination is fairly consistent. Among them, that between the visual control vertical and the vertical meridians of the eyes is probably the most important. This is due to the significance of the vertical direction in human orientation. When a subject's head is upright, the vertical direction and the median line of the head are approximately aligned with the vertical meridians of the eyes; and the tilt of a visual line from the vertical or from the median line of the head is well represented by the angle between its image meridians and the vertical meridians of the eyes. Therefore, a human subject should be able to make a fairly good estimate of the angle between a visual line and the vertical, or the median line of the head, by knowing in what meridians the images of the visual line lie.

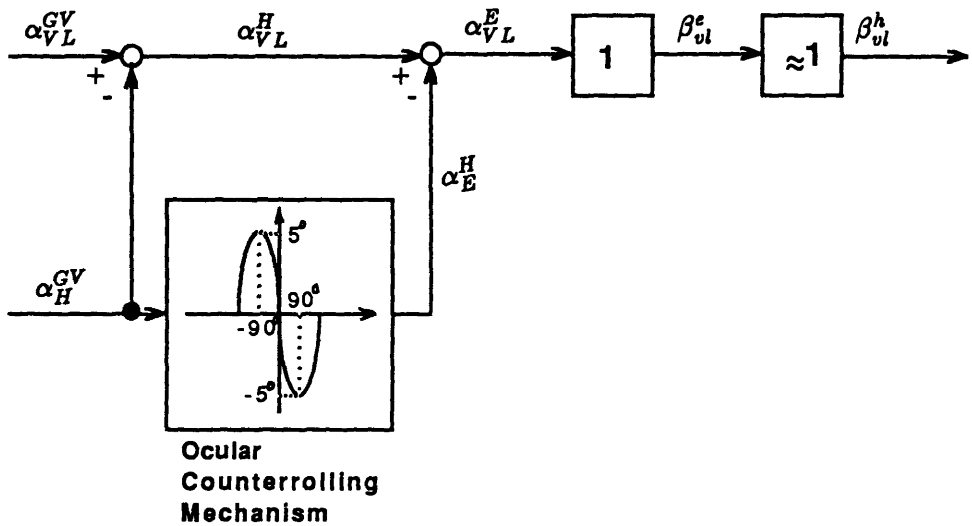


Figure 3.10: Control diagram of the *Visual Inclination Perception Mechanism*

But when a subject's head is tilted to the side (roll), the eyes do not tilt as far as the head. It appears that the eyes counterroll relative to the head. This is known as *ocular counterrolling*. The rolling of each eye is approximately a sine function of the overall head tilt. For a 90^o head tilt, the magnitudes are about 5^o [48,37] ([37] is also cited by Howard and Templeton on page 50 in [15]). The angle between the visual line (and thus its retina images) and the vertical meridian is not the same as the angle between the visual line and the median line of the head (see figure 3.10). It is assumed that the *ocular counterrollings* are not registered in the CNS and hence not compensated for. Therefore, the perceived angle between the visual line and the vertical meridians of the eyes is interpreted as the angle between the visual line and the median line of the head. Therefore, a visual inclination perceptual bias is introduced by the amount of *ocular counterrolling.*

The experiment conducted by Wade in 1970 [51] indeed showed that the *ocular counterrolling* is incorrectly, if at all, registered in the CNS. In his experiment, a subject was required to set a visual line to the median plane of the head with the head tilted 40^o relative to the torso, and with the torso in erect and supine positions. In the erect torso position, a 40^o head tilt stimulated the otolith organs and should introduce an approximately 4^o ocular torsion; whereas in the supine position no torsion of the eyes should be produced since the otolith organs were subjected to little or no stimulation due to the head tilt. If the ocular counterrollings are correctly registered in the CNS and compensated for, the subject's indications should be the same in these two body positions. If, as assumed, the counterrollings are not registered and thus not compensated for, the subject's indications should show the difference. The results suggested the latter. The indicated median plane of the head was displaced about 4^o in the direction of the torso when the torso was erect, and very little when the torso was in the supine position. These results strongly corroborated the assumption that the ocular counterrollings are incorrectly registered in the CNS, if at all. The consequence is that the perception of the angle between the visual line and the median line of the head is biased when the head is tilted (see figure 3.10). The perceptual bias caused by the ocular counterrolling is toward the same side as the head tilt. This means that the visual line is perceived as tilted more from the vertical than it actually is—when it is tilted in the same direction as the head tilt. When the line is tilted in the opposite direction to the head tilt it is perceived as being tilted less. This perceptual bias should in turn affect the VSV inclinations.

Figure 3.11 illustrates the entire VSV indication process. Suppose that the initial inclination of the visual line indicator is $(\alpha_{VL}^{GV})_0$ (figure 3.12 (a)), and the subject's torso and head are tilted α_T^{GV} and α_H^T degrees. The inclination of the visual line indicator in the head coordinates is then the difference between $(\alpha_{VL}^{GV})_0$ and α_H^{GV}:

$$\alpha_{VL}^{H} = (\alpha_{VL}^{GV})_0 - \alpha_H^{GV}.$$

It is a linear function of the overall head tilts with a slope of -1 and intercept of $(\alpha_{VL}^{GV})_0$ (see figure 3.12 (b)). Subtracting the *ocular counterrolling* α_E^H gives the

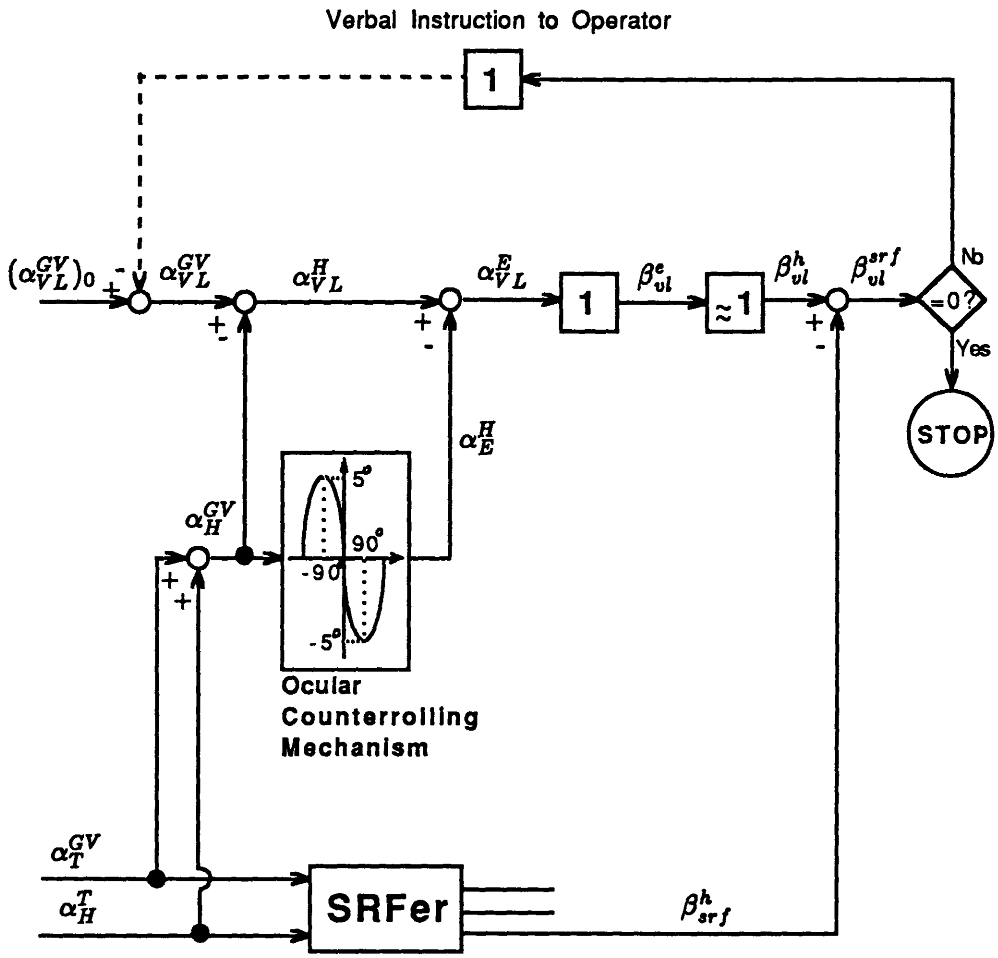


Figure 3.11: Illustration of entire VSV indication model

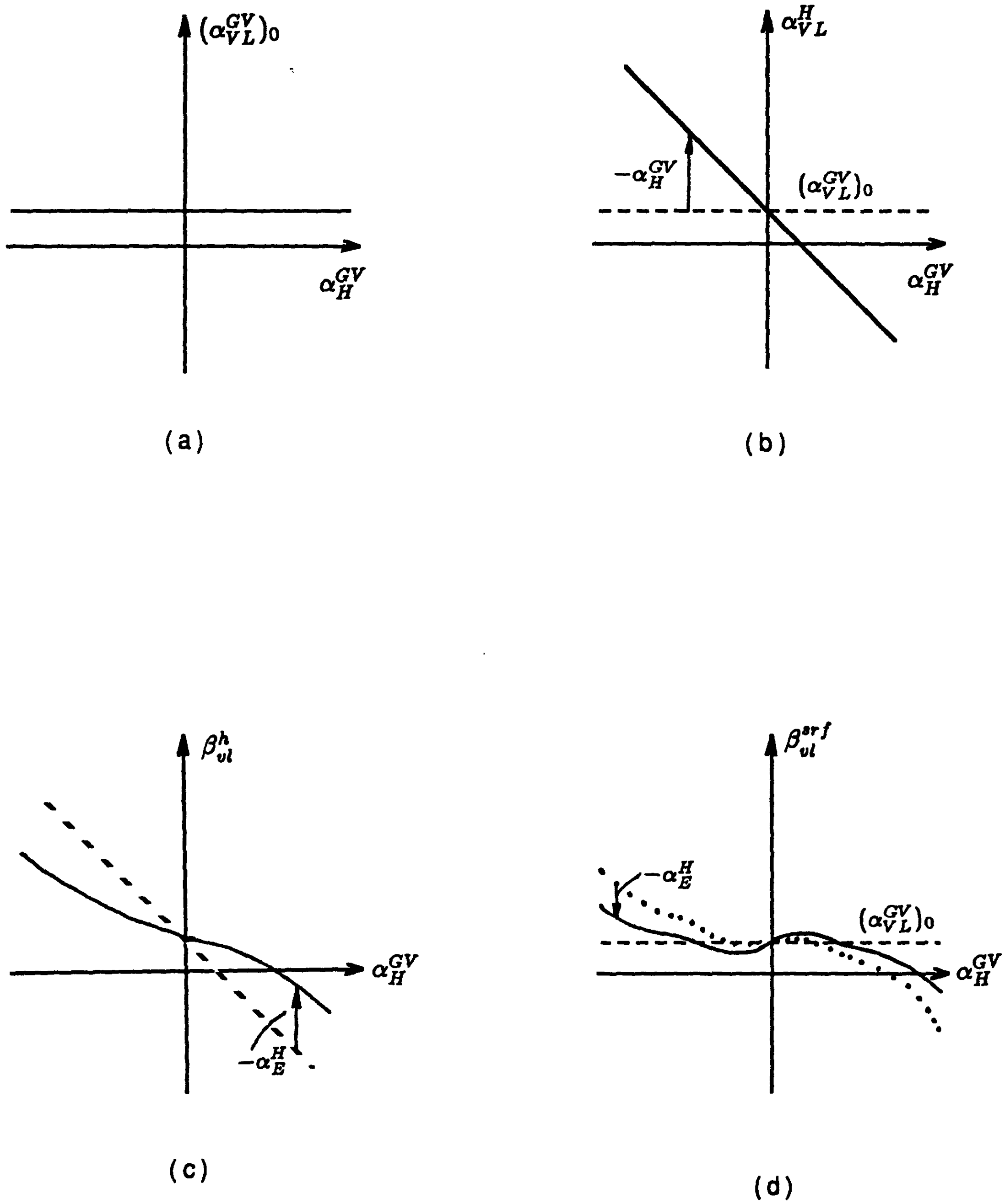
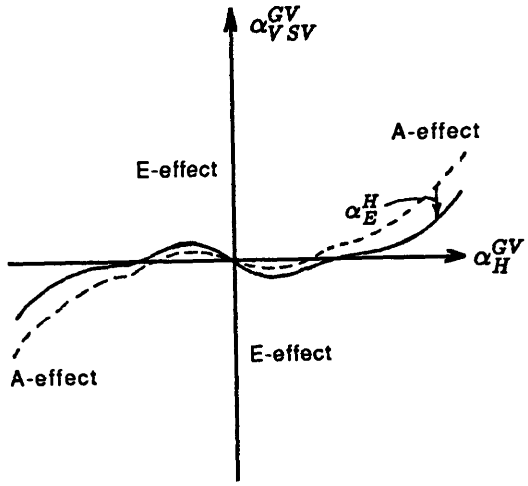


Figure 3.12: Outputs of VSV indication model (continued ...)



(e)

Figure 3.12: Outputs of VSV indication model (End)

For a detailed meaning of the symbols, refer to the "List of Symbols" on page 7.

(a) The initial inclination of the visual line indicator. (b) The initial inclination of the visual line indicator in the head coordinates. The broken line represents the initial inclination of the visual line indicator. (c) The initial inclination of the visual line indicator in the eye coordinates. It is also the perceived inclination of the visual line indicator in the head coordinates. The broken line represents α_{VL}^{H}. (d) Perceived inclination of the visual line indicator in the SRF coordinates. The broken line still represents the initial position of the visual line indicator; the dotted curve represents the would-be perceptions if the ocular counterrollings are compensated for. (e) The final VSV indications: the angle between the indicator and the vertical as a function of the overall head tilt. The broken line represents the would-be VSV indications if the ocular counterrollings are compensated for.

inclination of the visual line in the eye coordinates α^E_{VL}. Therefore, we have

$$\begin{aligned} \alpha^E_{VL} &= \alpha^H_{VL} - \alpha^H_E \\ &= (\alpha^{GV}_{VL})_0 - \alpha^{GV}_H - \alpha^H_E. \end{aligned}$$

In figure 3.12 (c)), the broken line with a slope of -1 represents α^H_{VL}, and the solid line represents α^E_{VL}. Their difference, $-\alpha^H_E$, is marked by an arrow. With the unit gains, we further have the perceived inclination of the visual line indicator in the eye and head coordinates β^e_{vl} and β^h_{vl}. Then this quantity is converted into SRF coordinates β^{srf}_{vl} (figure 3.12 (d)) by subtracting the constructed SRF z-axis in the head coordinates in figure 3.8 (c). The horizontal broken line still represents the initial position of the visual line indicator. The solid line represents the perceived inclination of the visual line in the SRF coordinates. The dotted line represents the would-be perception of the tilt if the ocular counterrollings are compensated for. The arrow marked $-\alpha^H_E$ indicates the contribution of the ocular torsion to the perception of the tilt of the visual line indicator. If this value is not zero, it is negatively fed back by the subject's instruction to alter the position of the visual line indicator. Therefore, subtracting these perceived tilts from the initial inclination of the indicator $(\alpha^{GV}_{VL})_0$ yields the final setting, i.e. VSV indication. Figure 3.12 (e) illustrates the indication errors as a function of the overall head tilt. The dotted curve denoted the would-be indications if the ocular counterrollings are compensated for.

Therefore, occurrences of the A-and E-effects in the visual verticality indications are determined by the ocular counterrollings of the eyes, the saturation characteristics of the sensory end organs for large tilts, and the central bias, and conservatism properties of the SRF-constructor. The saturation, central bias and conservatism are reflected in the shape of the dotted line (also see section 3.1). The model predicts that, in general, *E-effects vs. control* should occur for small tilts and *A-effects vs. control* should occur for larger ones. The E-effects should be enhanced by the ocular counterrolling.

It should be noted that the vertical meridians of the eyes do not always correspond to the vertical, because of the dynamic nature of human behavior and the asymmetry of human posture. Postural asymmetry can impose a basic bias on the visual indications of the vertical; the dynamic nature of a human's behavior must be partially responsible for the basic variability of the indications. This basic bias and variability is exhibited in the subject's indications when the head/body are in the upright position. They are referred to as the *control indication of the vertical* and *control variance*. This argument also suggests that the control indication is a better reference for the classification of the *"A- and E-effects"* than the true vertical.

3.3 Visual Subjective Torso (VST) indication process

The task of VST indication is to indicate the torso position when the subject's body (torso and/or head) is tilted. The scheme of the indication is hypothesized as in figure 3.13. The process is very similar to that of VSV indication except for the final comparison and the feedback. In the VSV indication process, the comparison is made between the perceived tilt of the visual line in SRF space β_{vl}^{srf} and zero since the vertical is to be indicated. But in VST indication process, β_{vl}^{srf} is compared with the perceived tilt of the torso from the control vertical β_t^{cv} and the feedback is the difference between the two. This is the only difference between VST and VSV indication processes, and it will create a surprisingly unexpected result.

Since most parts of this model are the same as in both VSV indication and SRF models, which have been discussed earlier, attention will be focused on the final comparison and the feedback loop only. Assume that the subject's torso and head are tilted at the angles of α_T^{GV} and α_H^T and the initial position of the visual line is $(\alpha_{VL}^{GV})_0$. Then, as discussed in the previous two sections, we know that the perceived tilt of the visual line in the SRF coordinates β_{vl}^{srf} and the perceived torso tilt β_t^{cv} are illustrated in (a) and (b) in figure 3.14. In figure 3.14 (b), the broken line with a slope of less than 1 represents the actual tilt of the torso from the gravitational vertical. As discussed earlier on page 103, a subject tends to overestimate the tilt of his torso tilt. The solid, saturated line represents the perception of the torso tilt (also see figure 3.6). The difference, i.e. the feedback, is illustrated in

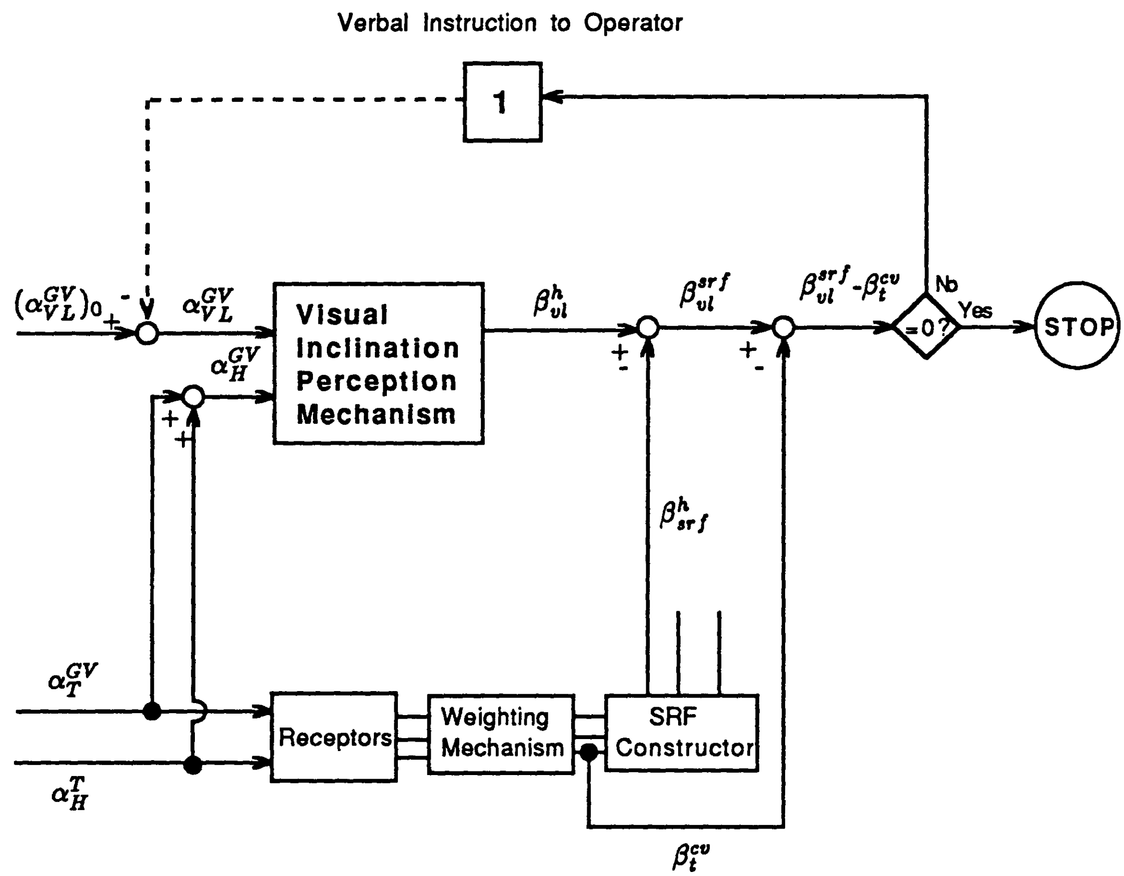


Figure 3.13: Illustration of the VST indication process

The broken line in the feedback path means that the subject himself does not have physical contact with the visual line indicator.

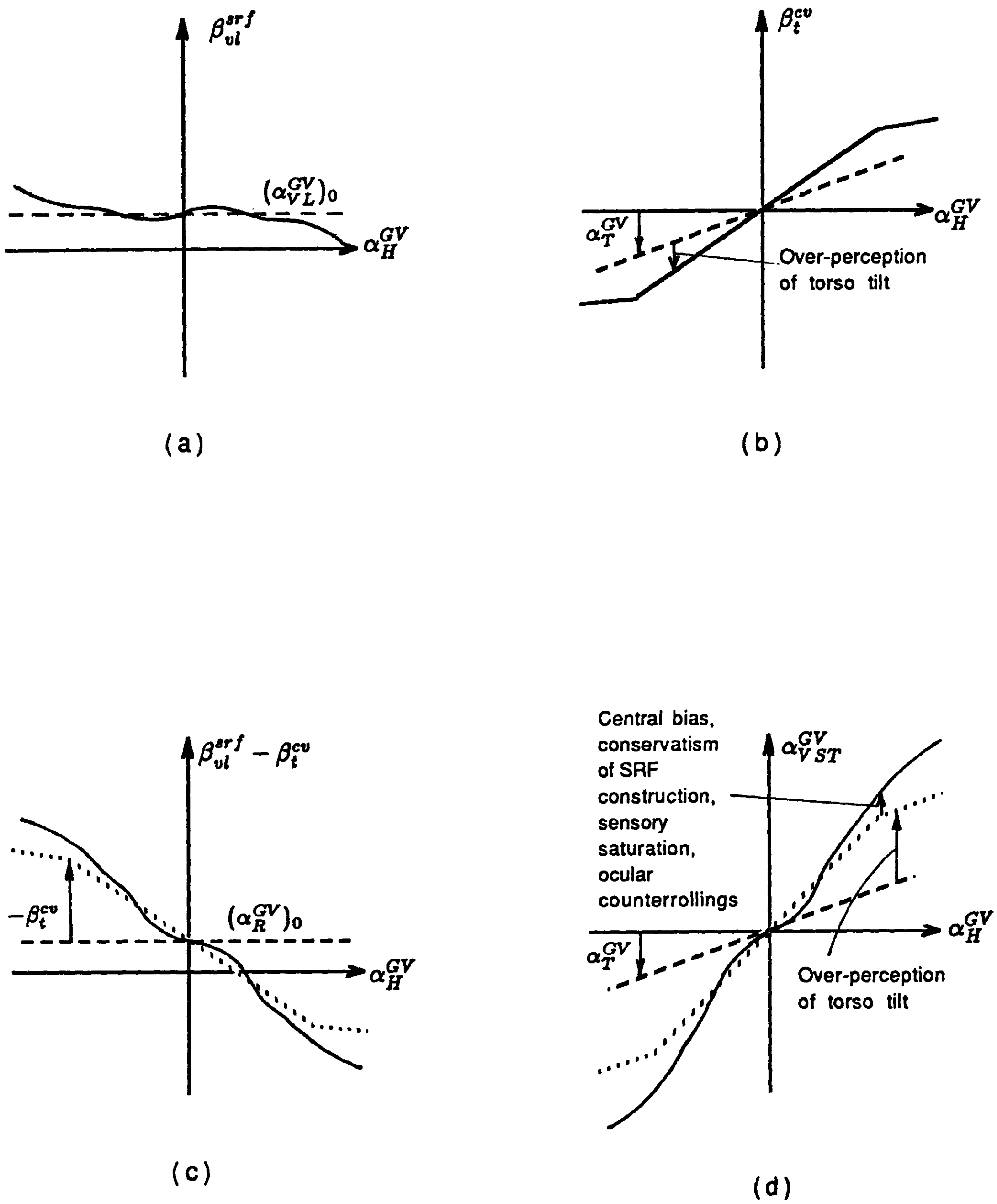


Figure 3.14: Outputs of VST indication model (continued ...)

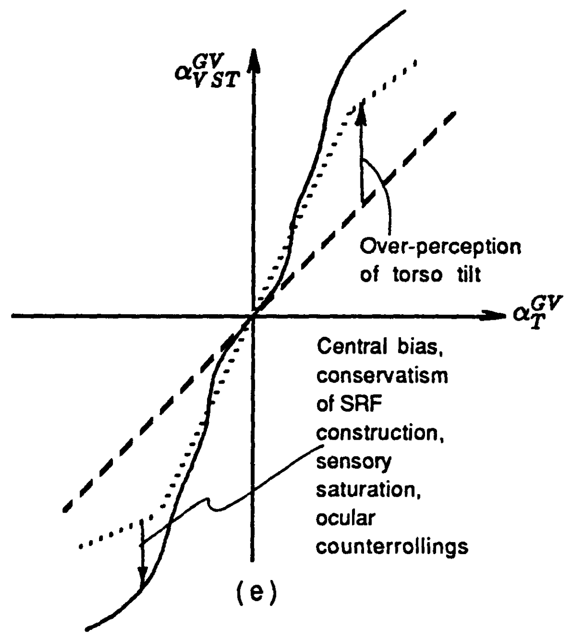


Figure 3.14: Outputs of VST indication model (End)

The meanings of the symbols are listed in "List of Symbols" on page 7: (a) perceived position of the visual line in the SRF coordinates as a function of the overall head tilt; The broken, horizontal line represents the initial position of the visual line indicator $(\alpha^{GV}_{VL})_0$. (b) perceived tilt of the torso relative to the control vertical as a function of the head tilt; The broken line represents the tilt of the torso from the vertical α^{GV}_{T}; the difference between the solid and broken lines is the over-perception of the torso tilt. (c) difference between (a) and (b) as a function of the overall head tilt; The broken, horizontal line represents the initial position of the visual line indicator $(\alpha^{GV}_{VL})_0$; the saturated, dotted line represents the contribution from β^{cv}_{t}. (d) VST indication as a function of the overall head tilt; The broken line represents the tilt of the torso; the saturated, dotted line represents the perception of the torso tilt. (e) VST indication as a function of the torso tilt. The broken line has a unity slope, representing a would-be accurate indication of the torso tilt; the saturated, dotted line represents the perception of the torso tilt.

figure 3.14(c). The horizontal line still represents the initial position of the visual line indicator. The saturated, dotted line represents the contribution of β_t^{cv} in figure 3.14 (b). The solid curve is the difference between the two . When this difference is negatively fed back, we have the final VST indications as a function of the overall head tilts (figure 3.14 (d)). The broken line marked α_T^{GV} represents the would-be faithful indication of the torso positions. The solid curve is the final VST indications. Therefore, one can see that sensory saturations, central bias, and conservatism properties of SRF construction, along with the uncompensated ocular counterrolling of the eyes, further bias the VST indications. The major bias is caused by the over-perceptions of the torso tilts. Figure 3.14 (e) shows the same indications as a function of the torso tilt relative to the gravitational vertical. It shows that the tilt of the torso is always over-indicated and thus is consistent with the observations discussed on page 103.

It is very surprising that, for the same body tilt, a subject is expected to show A- and E-effect when indicating the vertical–yet always show an over-indication (analogous to an A-effect) when indicating the torso position. Although it seems odd, the same results were actually obtained by Bauermeister [2]. This model suggests that it is the over-perception of the torso tilt that makes the VST indications surprisingly different from the VSV indications.

3.4 KSV indication process

In the KSV experiment a subject perceives the tilt of his torso, head, and the inclination of the *RP Indicator* relative to his torso. The former tilts are processed to yield the *SRF*, and the latter is converted into an inclination quantity in that frame (referred to as *Subjective Inclination* from now on). The objective of the task is to align the perceived *RP Indicator* with the z-axis of the *SRF*. Stated in another way, the task is to set the Subjective Inclination of the *RP Indicator* to zero (see figure 3.15).

In this model, the key element is the *Rod Inclination Perception Mechanism*. The inclination of the Rod Indicator is sensed by the operating hands that are directly connected to the subjects' torso. Thus it is assumed that the angle between the Rod Indicator and the torso is directly perceived. The process is denoted by the *Rod Inclination Perception Mechanism.*

The indication biases in the KSV, IIUH and VKSIM experiments suggest that the perceived inclination of the Rod Indicator is biased by the tilts of the head and torso, and the operating hand(s). Therefore, in this model, the Rod Inclination Perception Mechanism not only takes the physical inclination of the rod α_R^{GV} but also the tilts of the torso α_T^{GV} and head α_H^T and operating hand(s) as its inputs. For clarity, the biases are classified into three types and represented by the three biasers called *Hand Biaser*, *Neck Biaser* and *Torso Biaser* (see figure 3.16). The outputs of these biasers are therefore called *hand bias* S_{hb}, *neck bias* S_{nb} and *torso bias* S_{tb}.

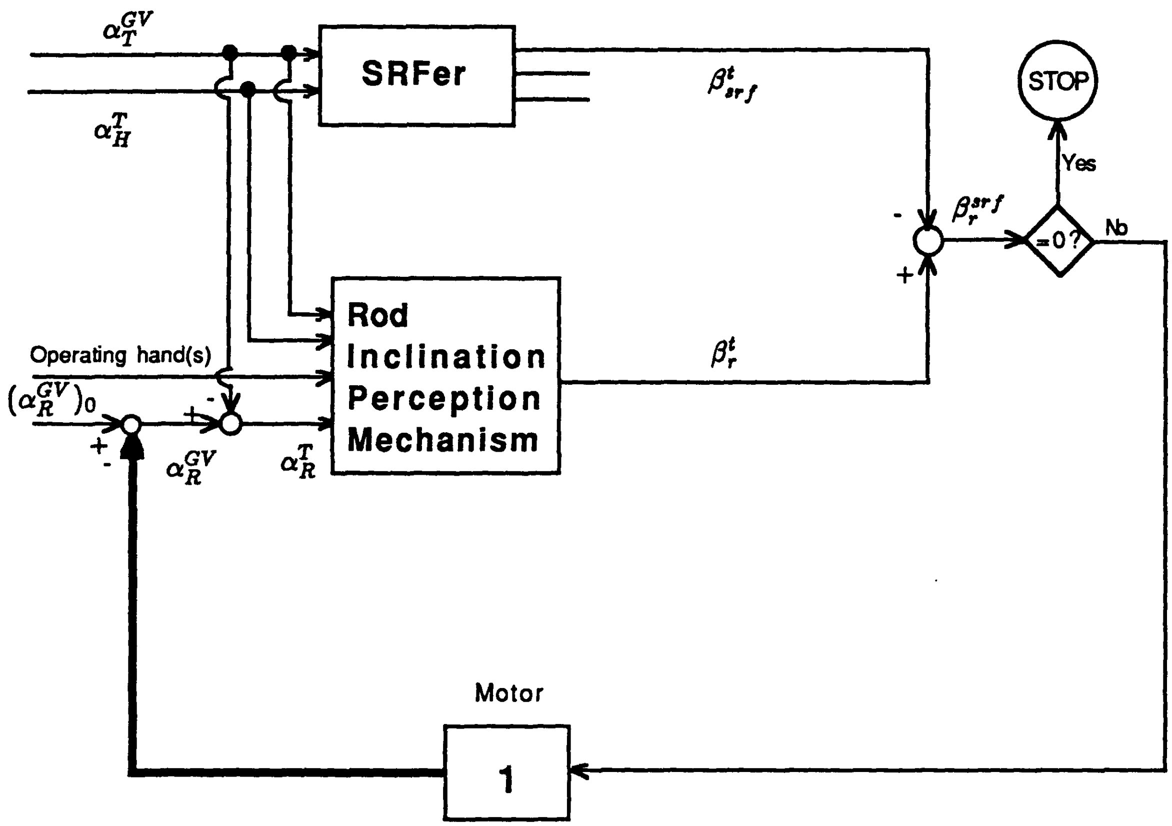


Figure 3.15: Control diagram of KSV indication process

The thick line in the feedback path means that the subject physically maneuvers the Rod Indicator.

The sum total of these biases is called the *total kinesthetic perceptual bias* denoted by S_{kb}.

The hand bias occurs when a single hand is used for indication. When the indicator is pivoted, this bias is toward the operating hand and, consequently, the indication is biased toward the non-operating hand. In other words, when the rod is tilted toward the side of the operating hand, the angle between the rod and a subject's torso is over-perceived; when the rod is tilted toward the side of the non-dominant hand, the angle is under-perceived. This bias can be reduced or eliminated by the use of both hands. This was clearly illustrated by the results of Bauermeister, et al. (1963)[3]. It is represented by the Hand Biaser in figure 3.16. When both hands are used there is no hand bias—the bias signal S_{hb} is zero. Otherwise, the bias is either positive or negative when either the dominant hand (DH) or non-dominant hand (NDH) is used.

The neck bias is caused by a head tilt, i.e., neck bending. When an indicator is tilted from the mid-line of the torso in the direction opposite to the tilt of a subject's head from the vertical, the subject always under-perceives the angle between the rod and torso. Consequently, when asked to indicate the angle, he always over-indicates it. On the other hand, the subject over-perceives the angle if the indicator is further tilted from the torso in the same direction as the tilt of the head from the vertical. When asked to indicate the angle, he always under-indicates it. In a word, the neck bias is towards the side of the head tilt. Consequently, when a subject is asked to indicate an inclination, his indications are always biased in the direction opposite

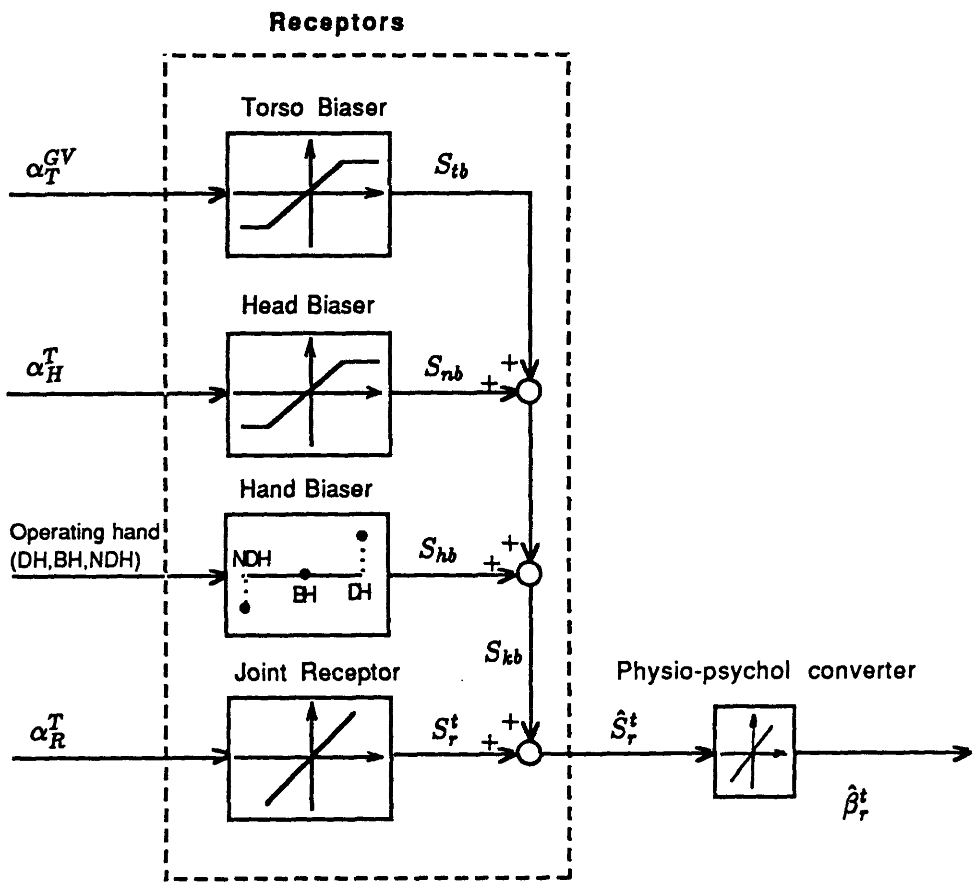


Figure 3.16: Block diagram of *Rod Inclination Perception Mechanism*

to his head tilt.

The torso bias is virtually the same as the neck bias, with only one distinction: it is caused by a torso tilt or torso bending. The output of all the biasers are expressed as physiological signals S_{hb}, S_{nb} and S_{tb}. Also notice that the last two biasers have the characteristic of saturation for large tilts. This will be explained in more detail in the next paragraph.

The rationale behind these biases is straightforward. The position of the rod is sensed by the proprioceptive sensory system. Due to exposure to the external world, this system is quite noisy. This is reflected in the large variability of the KSV, IIUH and VKSIM indications. Manipulating the indicators by a single operating hand requires an uneven neuro-muscular involvement. These uneven neuro-muscular activities impose an asymmetrical stimulation to the kinesthetic sensory system. The head or torso tilts, especially with the neck or torso bent or twisted, massively and unevenly stimulate the kinesthetic sensory system. These massive, uneven neuro-muscular activities produce large kinesthetic perceptual biases. The massive stimulation to the system also raises the noise level in the system, thus increasing the uncertainty of the perception of the rod inclination, which in turn increases the variability of KSV indications.

As discussed previously, neuro-muscular activities do not respond linearly to large muscular stimuli, and thus they saturate. Therefore, the Neck and Torso Biasers should have the same saturation characteristics too (figure 3.16).

The centerpiece in the Rod Inclination Receptor should be the Joint Receptors, which actually transfer the physical quantity α_R^T into the physiological signal S_r^t. As discussed earlier, the joint angle belongs to the metathetic continuum. Therefore, the joint receptors should have linear input-output relations. As also discussed previously, the slope of the input-output relationship is meaningless because it totally depends upon the unit chosen.

If there is no kinesthetic perceptual bias the physiological signal S_r^t is then transfered into a psychological entity called the "perceived tilt of the rod relative to the torso", i.e. β_r^t. But because of the biases, this S_r^t is modulated or biased and becomes $\hat{S}_r^t$ such that

$$\begin{aligned}\hat{S}_r^t &= S_r^t + S_{kb} \\ &= S_r^t + (S_{hb} + S_{bn} + S_{tb}).\end{aligned}$$

Then this modulated or biased signal is transfered into the perception β_r^t. This perception is of course modulated or biased. This modulation or bias will, in turn, manifest itself as an indication bias.

The element between $\hat{S}_r^t$ and β_r^t is a physio-psychological converter which converts a physiological input into a psychological perception. Since the perceptual continuum is *metathetic*, this physio-psychological converter should also be linear. Notice that the gain of the converter is not known. Based on the results of IIUH experiments we can hypothesize that the total gain between α_R^T and β_r^t is about 1. The perceived tilt of the rod relative to the torso is then converted into an inclination in the SRF β_r^{srf}. If this β_r^{srf} is not zero, the CNS commands the motor system to rotate the rod Indicator until β_r^{srf} reaches zero. The true position of the rod is the kinesthetic indication of the vertical.

This entire model is illustrated in figure 3.17.

Now let us put an illustrative example through the model in figure 3.17. Suppose the rod has an initial inclination $(\alpha_R^{GV})_0$ (figure 3.18 (a)), then its inclination in the torso coordinates $(\alpha_R^T)_0$ will be the difference between $(\alpha_R^{GV})_0$ and the subject's torso tilt:

$$\alpha_R^T = (\alpha_R^{GV})_0 - \alpha_H^{GV}.$$

This is a function of the torso tilt (figure 3.18 (b)). In this figure, the broken, horizontal line represents the initial position of the rod $(\alpha_R^{GV})_0$. Then the output of the Joint Receptor is S_r^t as illustrated in figure 3.18 (c). Where S_r^t has two parts S_r^{gv} and S_t^{gv}, S_r^{gv} corresponds to the initial rod position $(\alpha_R^{GV})_0$, and S_t^{gv} corresponds to the tilt of the torso α_T^{GV}. Since

$$(\alpha_R^T)_0 = (\alpha_R^{GV})_0 - \alpha_T^{GV}$$

and a linear transformation is assumed for the joint receptors,

$$S_r^t = S_r^{gv} - S_t^{gv}.$$

Assume both hands are used for indication—thus hand bias S_{hb} is zero. The resultant kinesthetic perceptual bias S_{kb} is therefore a linear function of the torso/head tilts α_H^{GV} (figure 3.18 (d)). The sum of S_r^t and S_{kb} is (e), which is the modulated or biased physiological response indicating $(\alpha_R^T)_0$. Thus

$$\hat{S}_r^t = S_r^t + S_{kb}$$

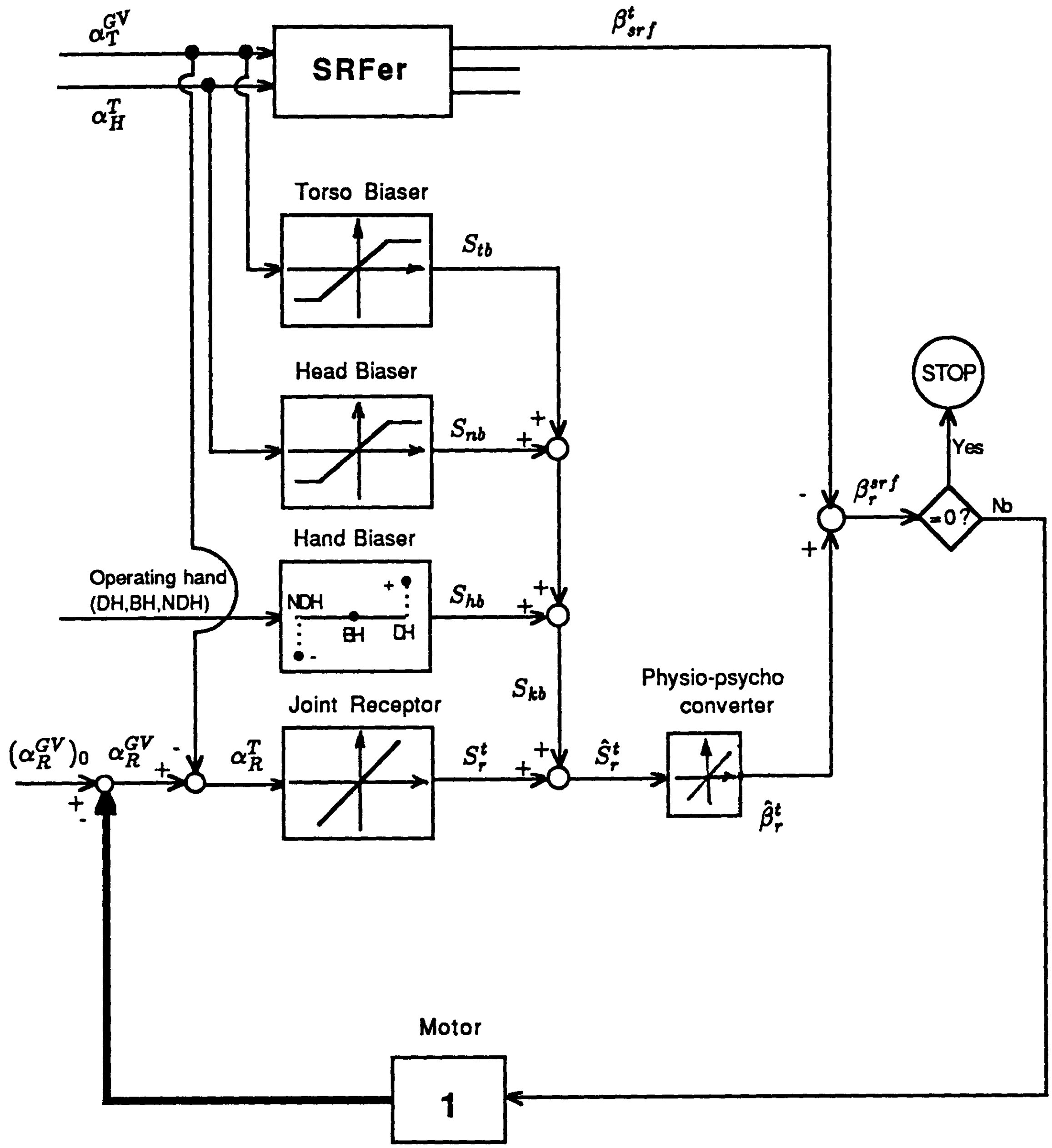


Figure 3.17: Illustration of the entire KSV indication model

$$= S_r^{gv} - S_t^{gv} + S_{kb}.$$

In figure 3.18 (e), the broken line represents S_r^t, the difference between the solid line and the broken line represents S_{kb}. This biased signal produces the biased perception of the tilt of the rod in the torso coordinates, $\hat{\beta}_r^t$, by passing through the linear physio-psychological converter.

This perception includes two parts in association with S_r^t and S_{kb} respectively:

$$\hat{\beta}_r^t = \beta_r^t + \beta_{kb}.$$

As hypothesized, the total gain between α_R^T and β_r^t is about one unit. Therefore, we have

$$\begin{aligned} \beta_r^t &= (\alpha_R^T)_0 \\ &= (\alpha_R^{GV})_0 - \alpha_T^{GV}. \end{aligned}$$

Therefore, we have

$$\begin{aligned} \hat{\beta}_r^t &= \alpha_R^T + \beta_{kb} \\ &= (\alpha_R^{GV})_0 - \alpha_T^{GV} + \beta_{kb}. \end{aligned}$$

This is illustrated in figure 3.18 (f), where the broken, horizontal line represents the contribution from the initial rod position and the dotted line represents the contribution from the torso tilts. Subtracting the constructed z-axis in the torso coordinates, β_{srf}^t (figure 3.8 (a)), yields the perceived inclination of the rod in the SRF coordinates (see figure 3.18 (g)). Where the broken, horizontal line represents the contribution from the initial rod position, and the saturated, dotted line represents the contribution from S_{kb}. When this value is not zero, it is negatively fed back by muscular manipulation of the rod. Therefore, subtracting it from the initial rod inclination (in (a)) gives the final setting, i.e. the kinesthetic indication of the vertical. Figure 3.18 (h) illustrates the indication errors as a function of the overall head tilts. Therefore, *E-effects vs. control* are expected throughout the tilts (from 0^o to $\pm 90^o$).

One can see that it is the kinesthetic bias α_{KB} that makes the KSV indications dramatically different from the VSV indications. As discussed earlier, this bias is generated by the tilts of the head and torso. When the tilts require actual bending of the waist, torso, and neck, the bias should be larger. A whole body tilt does not involve the bending of the neck, waist, or torso—therefore S_{nb} is zero and S_{tb} is small. In this case, the total kinesthetic bias S_{kb}, and thus α_{KB}, should be small. Thus the variability of the subject's indications should be small also, and the *E-effects vs. control* should be smaller. If this reduced kinesthetic bias is small enough, an A-effects control may occur for a small or approximately horizontal tilt. This is especially true in the case of a single operating hand when the body is tilted toward the side of the non-operating hand. In that case the hand kinesthetic bias increases the possibility of the occurrence of the A-effect vs. control. Bauermeister, *et al.* indeed found smaller kinesthetic E-effects vs. control with the subject's whole body tilted, and A-effects vs. control with a single operating hand and the appropriate body tilt [3].

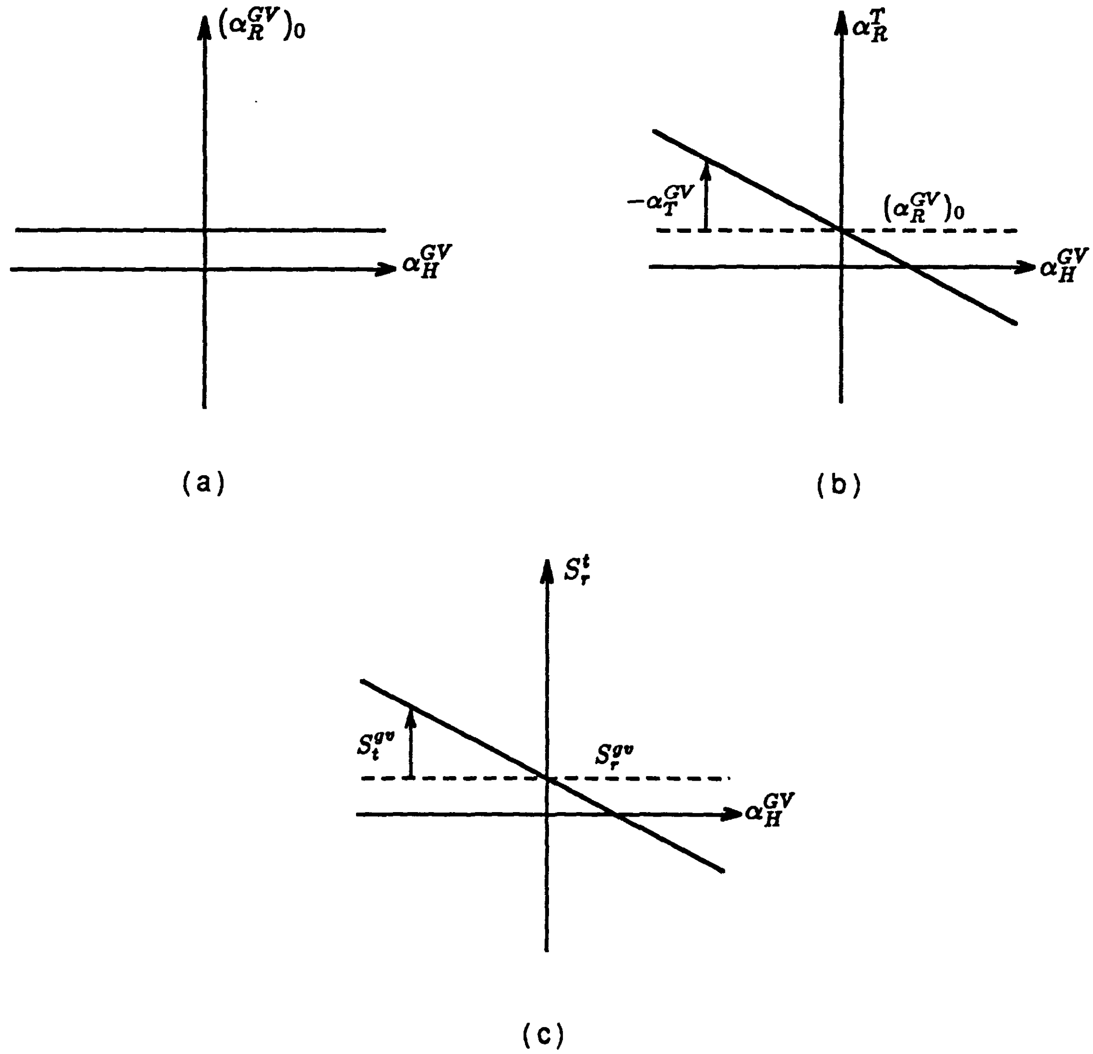
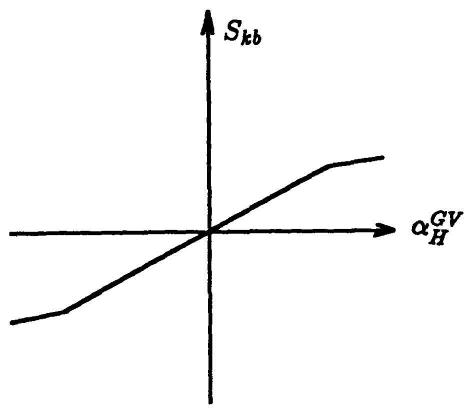


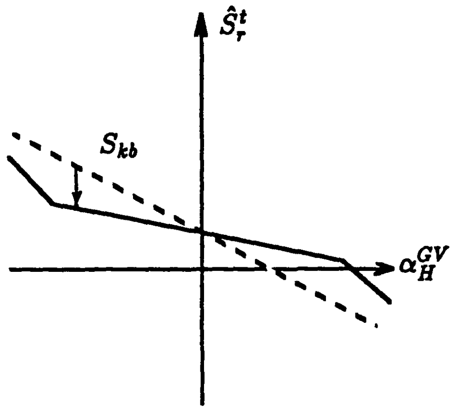
Figure 3.18: Outputs of KSV indication model (continued ...)

For a detailed meaning for the symbols, refer to the "List of Symbols" on page 7.

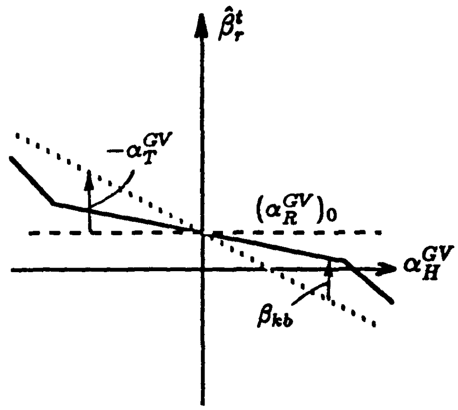
(a) The initial inclination of the rod. (b) The inclination of the rod in the torso coordinates as a function of the overall head tilt. The broken, horizontal line represents the initial position of the Rod Indicator. (c) The physiological outputs of the Joint Receptors. The broken, horizontal line represents the contribution from $(\alpha_R^{GV})_0$, the difference between the solid and broken lines represents the contribution from α_T^{GV}.



(d)



(e)



(f)

Figure 3.18: Outputs of KSV indication model (continued ...)

For a detailed meaning for the symbols, refer to the "List of Symbols" on page 7.
(d) The total kinesthetic bias (assume BH are used for indication, thus hand bias is zero). (e) Physiological signals representing the inclination of the rod in the torso coordinates as a function of the overall head tilt. The broken line represents S_r^t. (f) The biased perception of the tilt of the Rod Indicator relative to the torso. The broken, horizontal line represents the contribution of the initial position of the Rod Indicator; the dotted line represents the contribution of the torso tilt.

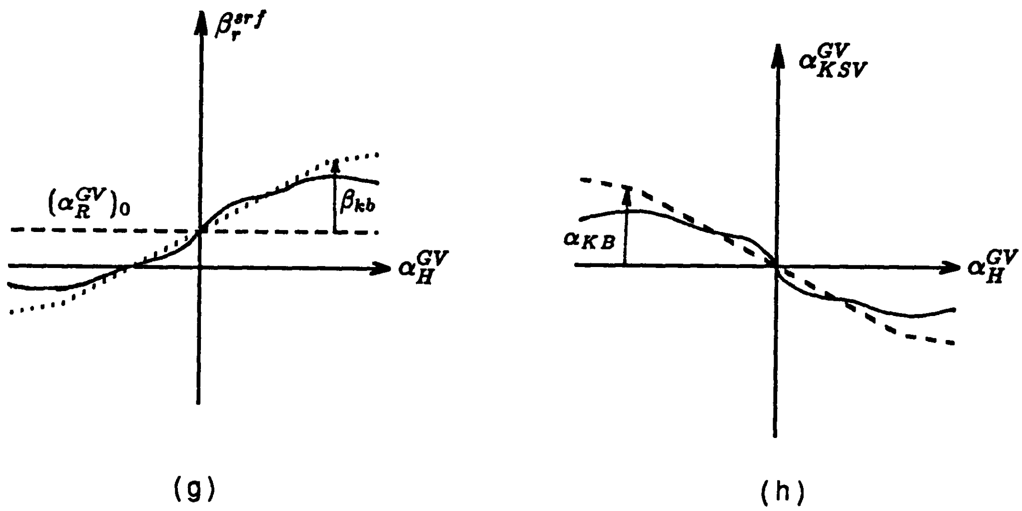


Figure 3.18: Outputs of KSV indication model (End)

For a detailed meaning for the symbols, refer to the "List of Symbols" on page 7.

(g) The perceived inclination of the rod in the SRF coordinates. The broken, horizontal line represents the contribution of the initial rod position; the dotted, saturated line represents the total kinesthetic perceptual bias. (h) The final settings of the vertical as a function of the overall tilt.

3.5 VKSIM indication process

In the VKSIM experiments, a subject receives information about his body status, the inclination of the visual line, and the Rod Indicator. The former is processed to construct the *SRF*, and the latter two are converted into the corresponding inclination quantities in the SRF space (referred to as Subjective Inclinations). The objective of the task is to match the subjective inclination of the Rod Indicator with that of the visual line, by manipulation of the Rod Indicator (see figure 3.19).

Let us use an example to explain the logic of this model. Suppose that the visual line is inclined α_{VL}^{GV} and that the Rod Indicator has the same initial inclination. From the previous discussion we know that the output of the Visual Inclination Receptor is the perceived inclination of the visual line in the head coordinates β_{vl}^{h} (see figure 3.9 and 3.12 (c)). Subtracting this from the perceived SRF z-axis in the same coordinates β_{srf}^{h} (figure 3.8 (c)) gives the perceived inclination of the visual line in the SRF coordinates β_{vl}^{srf} (figure 3.20 (a)). On the other hand, the output of the Rod Inclination Receptor is the perceived inclination of the Rod Indicator in the torso coordinates $\hat{\beta}_{r}^{t}$ (see figure 3.15 and figure 3.18 (f)). Subtracting the constructed SRF z-axis in torso coordinates β_{srf}^{t} (figure 3.8 (a)) yields the perceived inclination of the Rod Indicator in the SRF coordinates β_{r}^{srf} (see figure 3.20 (b)). The two perceived inclinations of the Rod indicator and the visual line are then compared. The difference is shown in figure 3.20 (c). The broken line represents the total kinesthetic perceptual bias, and the downward arrow marked α_{E}^{H} represents

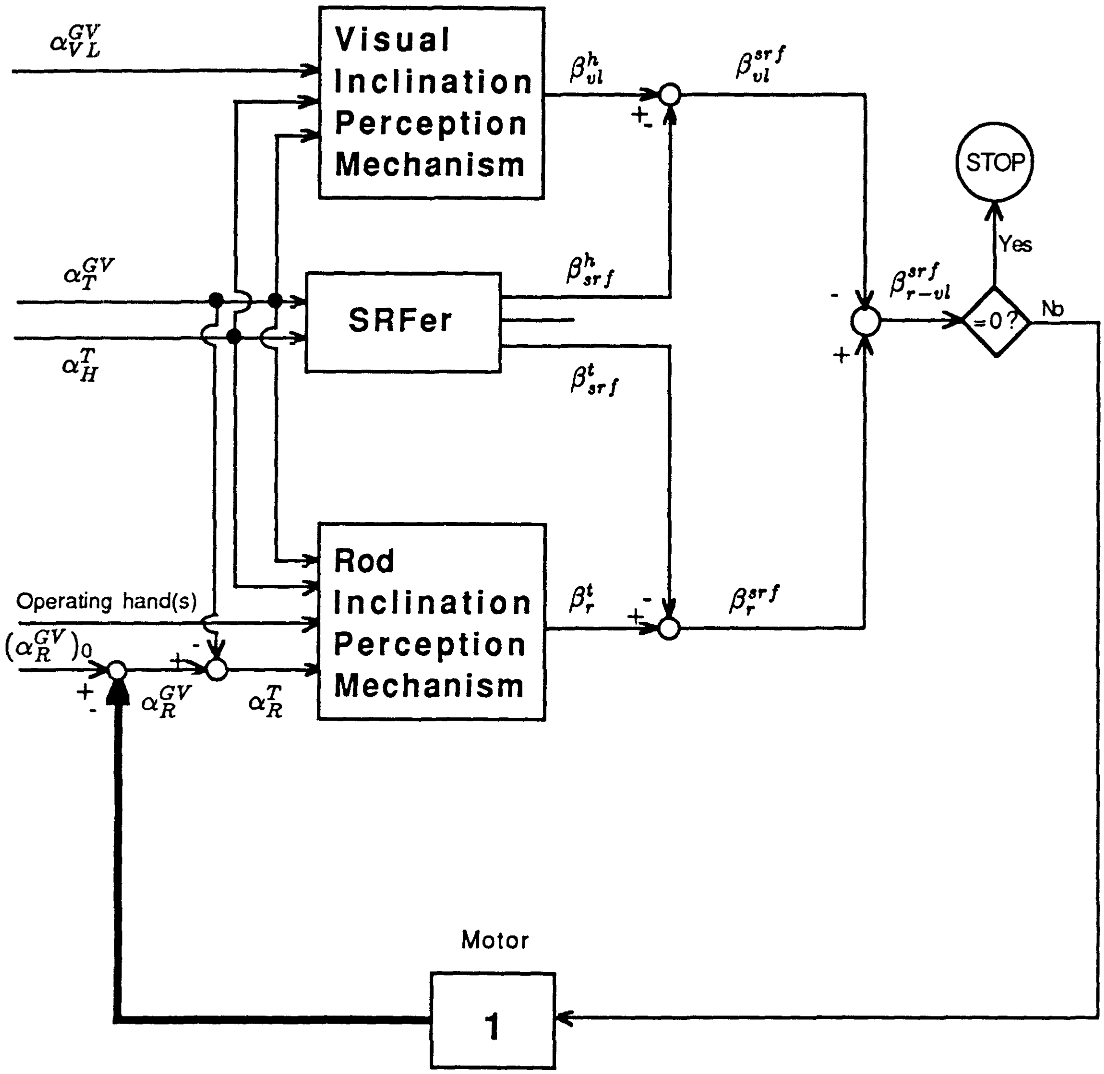


Figure 3.19: Control diagram of VKSIM indication process

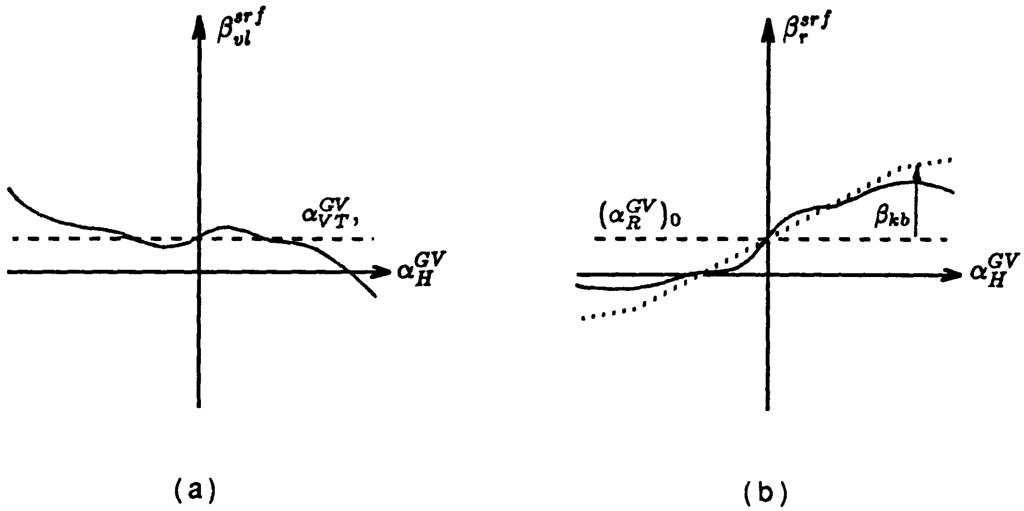


Figure 3.20: Outputs of VKSIM indication model (continued...)

For a detailed meaning for the symbols, refer to the "List of Symbols" on page 7.
(a) The perceived inclination of the visual line in the SRF. The broken, horizontal line represents the position of the visual line display. (b) The perceived inclination of the Rod Indicator in the SRF coordinates. The broken, horizontal line represents the initial position of the Rod Indicator and the saturated, dotted line represents the total kinesthetic perceptual bias.

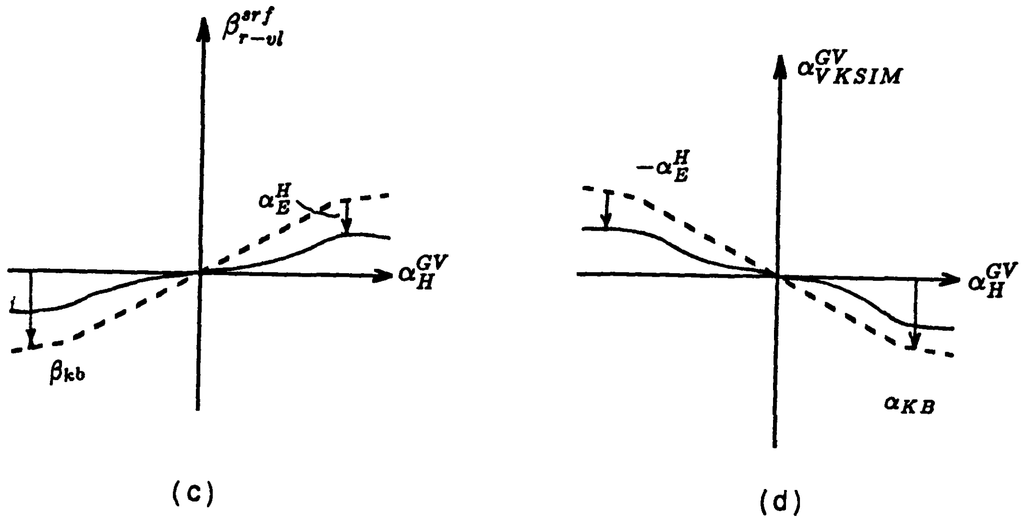


Figure 3.20: Outputs of VKSIM indication model (End)

For a detailed meaning for the symbols, refer to the "List of Symbols" on page 7. (c) The difference between the perceived inclinations of the Rod Indicator and the visual line in the SRF coordinates. The broken line represents the total kinesthetic perceptual bias, and the downward arrow marked α^H_E represents the contribution of the ocular counterrolling. (d) The final settings—the VKSIM-indication errors as a function of the overall head tilt. The broken line still represents the total kinesthetic perceptual bias, and the downward arrow marked α^H_E represents the contribution of the ocular counterrolling.

the contribution of ocular counterrolling. If this value is not zero, it is negatively fed back by muscular manipulation of the Rod Indicator. The final setting is shown in figure 3.20 (d). Thus, the VKSIM indications are always influenced by the kinesthetic biases and the the ocular counterrolling of the eyes. The *ocular counterrollings* impose a perceptual bias and hence a VKSIM-indication bias in the same direction as the tilts of the head and/or torso. The neck and torso kinesthetic biases tend to bias the VKSIM indications in the direction opposite to the tilt of the head and/or torso. Therefore, the effects of the ocular counterrollings and the kinesthetic biases are opposite. If the former has a greater effect than the latter, the resultant VKSIM-indication bias would be in the direction of the head/torso tilt, otherwise the resultant bias is in the opposite direction. Because neck and torso bendings is hypothesized to produce very large biases, this bias in the opposite direction is most likely to occur when either of those body postures are involved.

When the whole body is tilted (with the trunk remaining straight), the neck bias is zero and the torso bias is small. The resultant indication depends upon the relative magnitudes of this bias and the ocular counterrolling. For some body positions, the effects of the ocular counterrolling and the torso kinesthetic bias may have the same magnitudes and could thus cancel each other out. In those cases, the VKSIM indication would not be biased.

The results from VKSIM.II experiment with the whole body tilted 90° falls within this category. This does not mean that the horizontal body position is always the position where cancellation will occur. For a different subject and even at a different time for the same subject, the specific body position in which the cancellation occurs may change or be non-existent.

Chapter 4

Conclusion

Utilizing a series of experiments, this thesis has investigated human subjective indication of the vertical,. These experiments include the Kinesthetic Subjective Vertical (KSV, n=6 subjects), Inclination Indication with Unseen Hand(s) (IIUH, n=3 subjects), and Visual Kinesthetic Spatial Inclination Matching (VKSIM, n=2, 1, 1 respectively). The major conclusions are as follows:

In a room with normal light, visual and kinesthetic verticality indications are in good agreement when the subject is in the upright position. The IIUH experiment showed significant discrepancies, between the visual line displays and the kinesthetic indications, of about 2^o when a single hand was used for indication. When both hands are used no significant discrepancy was found. But the discrepancy between visual and kinesthetic indications seemed to increase in the dark. The VKSIM.I, II and III experiments indicated statistically significant discrepancies, which were 3^o–5^o.

When a subject's head was tilted to the side, the discrepancy increased dramatically. In the KSV experiment, when the subjects' heads were tilted 90^o toward the dominant hand, they showed significant *E-effects vs. control* of 18^o on average. When their heads tilted 90^o toward the side of the non-dominant hand they showed significant *E-effects vs. control* of 8^o on average. Significant and enormous E-effects found in this experiment contradict the results obtained in classic Visual Subjective Vertical (VSV) experiments, which were approximately 5^o A-effects.

In the VKSIM.I experiment, the subjects were asked to set a Rod Indicator parallel to luminous line displays. With their heads tilted 90^o to the side, their indications were significantly biased 17.69^o to 19.80^o from the luminous lines. The biases were consistently in the direction opposite to the tilt of their heads. The biases could account for the discrepancies found between our KSV indications and the classic VSV indications. I *believe* that these biases were generated kinesthetically. They include ***hand bias***, ***neck bias*** and ***torso bias***. The IIUH experiment showed significant hand bias of about 2^o. The results also suggested that when the indicator was pivoted, the direction of the hand bias was toward the side of the non-operating hand. When the indicator was held freehand, the KSV results suggested that the bias was toward the side of the operating hand. The IIUH experiment also showed that this bias was not significant, (on the average), when using both hands for indication.

The neck and torso biases are associated with neck and torso bending. Both the VKSIM.I and VKSIM.III experiment showed that when the head was tilted $\pm 90^o$, the mean indication error (reflecting the sum of the neck and torso biases) was highly significant. The magnitudes were approximately 20^o and the directions were always opposite to the tilt of the head and/or torso. Furthermore, the KSV experiment showed statistically significant interactions between the operating hand and the head tilt, i.e., between the hand bias and the head/torso bias. The interaction generated a significantly larger resultant bias (18°) when the head and/or torso were tilted toward the operating hand side. The resultant bias was smaller (8°) when the head and/or torso were tilted toward the non-operating hand side. The directions of the resultant biases were dominated by the neck and/or torso biases, i.e., toward the direction opposite to the side of the head and/or torso tilts.

The origin of these biases *is believed* to be associated with asymmetrical muscular involvement. This asymmetrical involvement *is expected* to be created either by using a single hand for indication or by a tilt of the head or torso.

The VKSIM.II did not show a significant indication error in the kinesthetic indications of a visual line when the subject's entire body was horizontal. The reason *is believed* to be that tilting the entire body does not produce massive assymetrical muscular involvement, and thus does not produce a large kinesthetic bias. The bias would be small enough to be canceled out by the effect of *ocular counterrolling*. This may be why the resultant VKSIM indication with the subject's entire body lying horizontally did not show significant bias. In addition, the subject did not show significant differences between his indications when lying on his left or right. Therefore, it was also concluded that the horizontal body position could be a basic orientation position, as is the upright, and that the subject might have a different orientation technique in the horizontal position.

In both the KSV and VKSIM.I experiments, the subjects showed significantly larger variances when their heads/torsos were tilted, as opposed to upright. However, in the VKSIM.II experiment, when the subject lay on a horizontal table, he did not show any significant increase of variance in the indications. In the VKISM.III experiment, where horizontal visual line displays were used, he showed a consistent tendency to increase the variance—but the increase was not statistically significant. The increased variance *is seen* as a consequence of the increased noise in the kinesthetic sensory system caused by the massive stimulation imposed by the head and torso tilts and the aysmmetrical head positions. The whole body tilt *is hypothesized* not to increase the uncertainty in the kinesthetic sensory system. The horizontal visual lines while sitting erect *are expected* to require more symmetrical involvement of the subject's operating hands, and this may explain why the variance was not significantly increased.

The IIUH and VKSIM.I, II and III experiments all showed that the subjects had significant tendencies to under-indicate the tilt of the 15^o inclined visual lines. Only one subject in the VKSIM.I showed a significantly opposite tendency, i.e., he tended to over-indicate the tilts.

Based on these results, a heuristic model was established to postulate the mechanism of human perception and indication of the vertical. The model divided the process into three phases: perception of the body's position, construction of a *Subjective Reference Frame (SRF)*, and the indication process. The indication process in turn had two sub-phases: perception and manipulation of an indicator. The indicator could be either a luminous line indicator or a rod indicator. The model used an unconventional concept of *Subjective Reference Frame (SRF)* to describe a subject's perception of the vertical. It was proposed that this SRF be established based on perceptions of the body's position and the subject's previous orientation experiences. It was postulated that a subject orients himself and external objects in his SRF. It offers an insight into the understanding of various intangible neurological events and psychological processes involved in human spatial orientation. This model is the first to pay attention to the differences between visual and kinesthetic orientation. It successfully explains many seemingly inconsistent experimental results obtained by either previous investigators or by us.

The model predicts that a human subject's perception of the vertical or the SRF z-axis varies with the tilts of the head and/or torso. For small tilts, the perceived vertical *is expected* to deviate from the true vertical to the side opposite to the tilt of the head and/or torso. For large tilts, it *is predicted* to deviate to the same side as the tilt.

The visual indication of the subjective vertical should differ from the perceived vertical, due to ocular counterrolling, despite the fact that they should have the same pattern. This means that VSV indications *are expected* to show *E-effects vs. control* for small tilts of the head and/or torso, and *A-effects vs. control* for larger tilts.

Surprisingly, the model predicts that if a subject had been asked to indicate the torso position, the indications *are expected* to be completely different from the VSV indications. Based on the proposed orientation scheme, the subjects *are expected* to always over indicate the tilt of the torso. This prediction could be tested.

Because of the large kinesthetic bias, the modeled kinesthetic vertical indications generally show *E-effects vs. control*, e.g. the indications should be biased from the true vertical to the side opposite to the head tilts. The kinesthetic indication of a visual target line is also generally expected to be biased to the side opposite to the head tilt for the same reason.

Whole body tilts differ somewhat from head tilts. The model predicts that whole body tilts produce smaller indication errors, since they do not generate large uneven neuro-muscular activities. Furthermore, in the case of kinesthetic indication of the vertical, an A-effect might occur for very small tilts of the head, or tilts near the horizontal. In the case of kinesthetic indication of a visual line, the indication error is reduced to zero when the whole body is upright or tilted to the horizontal position.

Further experiments should be carried on to determine the parameters of the proposed models. More data should be collected at different head and/or torso tilts. A quantitative expression of the perceived vertical (i.e. the position of the SRF z-axis in inertial coordinates) should be derived first. This can be done by subtracting the ocular counterrolling from the VSV indications. Therefore, a VSV indication experiment with simultaneous measurement of the ocular torsion is appropriate. With various combinations of the head tilts, torso tilts, and body positions (supine or normal), the parameters of the SRF model would be identifiable. Of course, caution must be taken to avoid interference between torsion measuring and visual perception.

As a result, additional experiments on KSV or VKSIM will yield the kinesthetic biases as functions of the head and torso tilts.

A major pitfall in this research, however, is the large variabilities of subjects' indications. Analysis of variances usually showed that most inter-subject and inter-session variabilities were significant. This means that careful attention must be paid to experimental design—particularly to isolate the sources of inter-session and inter-subject variabilities. Larger populations of subjects should be used and better physical control of body tilt is recommended.

Appendix A

Original Data

A.1 Row data from KSV experiment

Subject #	Head Position	Indication (degree)
1	1	-16
1	1	-22
1	1	-17
1	1	-19
1	1	-19
1	1	-19
1	2	1
1	2	2
1	2	1
1	2	1
1	2	1
1	2	1
1	2	2
1	2	1
1	2	2
1	3	23
1	3	18
1	3	17
1	3	16
1	3	16
1	3	15
1	3	16

Subject #	Head Position	Indication (degree)
1	3	17
1	3	18
2	1	-22
2	1	-19
2	1	-22
2	1	-21
2	1	-19
2	1	-23
2	1	-23
2	1	-26
2	1	-17
2	2	2
2	2	6
2	2	1
2	2	3
2	2	4
2	2	1
2	2	5
2	2	0
2	2	8
2	3	6
2	3	5
2	3	5
2	3	4
2	3	0
2	3	-1
2	3	9
2	3	9
2	3	4
3	1	-16
3	1	-15
3	1	-12
3	1	-17
3	1	-11
3	1	-17
3	1	-10
3	1	-7
3	1	-11

Subject #	Head Position	Indication (degree)
3	2	5
3	2	4
3	2	5
3	2	6
3	2	4
3	2	4
3	2	2
3	2	4
3	2	4
3	3	12
3	3	13
3	3	17
3	3	10
3	3	11
3	3	11
3	3	10
3	3	13
3	3	11
4	1	-11
4	1	-11
4	1	-8
4	1	-10
4	1	-9
4	1	-15
4	1	-15
4	1	-14
4	1	-11
4	2	5
4	2	6
4	2	2
4	2	3
4	2	4
4	2	4
4	2	8
4	2	1
4	2	6
4	3	6
4	3	11

Subject #	Head Position	Indication (degree)
4	3	6
4	3	5
4	3	7
4	3	10
4	3	7
4	3	9
4	3	10
5	1	-9
5	1	-20
5	1	-21
5	1	-1
5	1	-12
5	1	-22
5	1	-19
5	1	-17
5	1	-19
5	2	-2
5	2	0
5	2	0
5	2	-1
5	2	0
5	2	-3
5	2	1
5	2	3
5	2	-3
5	3	13
5	3	12
5	3	13
5	3	15
5	3	22
5	3	11
5	3	11
5	3	7
5	3	15
6	1	-22
6	1	-9
6	1	-18
6	1	-14

Subject #	Head Position	Indication (degree)
6	1	-10
6	1	-7
6	1	-11
6	1	-9
6	1	-11
6	2	0
6	2	1
6	2	-1
6	2	-2
6	2	-1
6	2	-8
6	2	5
6	2	0
6	2	0
6	3	8
6	3	11
6	3	8
6	3	6
6	3	4
6	3	5
6	3	3
6	3	10
6	3	11

A.2 Raw data from IIUH experiment

Sub. #	Hand #	Tar. #	Reading in degree	error in degree
1	1	1	11	-4
1	1	1	11	-4
1	1	1	4	-11
1	1	2	7	7
1	1	2	-4	-4
1	1	2	-7	-7
1	1	3	-20	-5
1	1	3	-17	-2
1	1	3	-19	-4
1	2	1	6	-9
1	2	1	7	-8
1	2	1	5	-10
1	2	2	0	0
1	2	2	-2	-2
1	2	2	-4	-4
1	2	3	-12	3
1	2	3	-17	-2
1	2	3	-18	-3
1	3	1	14	-1
1	3	1	8	-7
1	3	1	8	-7
1	3	2	0	0
1	3	2	0	0
1	3	2	-2	-2
1	3	3	-11	4
1	3	3	-16	-1
1	3	3	-13	2
2	1	1	-13	-2
2	1	1	-18	3
2	1	1	-13	-2
2	1	2	4	-4
2	1	2	2	-2
2	1	2	-1	1
2	1	3	13	2
2	1	3	9	6
2	1	3	10	5
2	2	1	-15	0

2	2	1	-13	-2
2	2	1	-18	3
2	2	2	-5	5
2	2	2	0	0
2	2	2	1	-1
2	2	3	10	5
2	2	3	11	4
2	2	3	11	4
2	3	1	-15	0
2	3	1	-13	-2
2	3	1	-14	-1
2	3	2	-1	1
2	3	2	0	0
2	3	2	-3	3
2	3	3	11	4
2	3	3	6	9
2	3	3	9	6
3	1	1	14	-1
3	1	1	12	-3
3	1	1	14	-1
3	1	1	13	-2
3	1	1	12	-3
3	1	2	-1	-1
3	1	2	0	0
3	1	2	0	0
3	1	2	0	0
3	1	2	0	0
3	1	3	-16	-1
3	1	3	-17	-2
3	1	3	-14	1
3	1	3	-14	1
3	1	3	-10	5
3	2	1	16	1
3	2	1	17	2
3	2	1	10	-5
3	2	1	11	-4
3	2	1	12	-3
3	2	2	3	3
3	2	2	3	3
3	2	2	0	0
3	2	2	2	2
3	2	2	0	0

3	2	3	-19	-4
3	2	3	-14	1
3	2	3	-16	-1
3	2	3	-14	1
3	2	3	-16	-1
3	3	1	15	0
3	3	1	15	0
3	3	1	16	1
3	3	1	17	2
3	3	1	18	3
3	3	2	1	1
3	3	2	5	5
3	3	2	6	6
3	3	2	3	3
3	3	2	5	5
3	3	3	-12	3
3	3	3	-20	-5
3	3	3	-13	2
3	3	3	-9	6
3	3	3	-12	3

A.3 Raw data from VKSIM.I experiment

Subject #	Session #	Head tilt	Target tilt	Reading (volt)	Error (deg)	Modified error (deg)
1	1	1	1	-0.08	-17.83	-17.83
1	1	1	1	-0.10	-18.52	-18.52
1	1	1	1	-0.26	-24.08	-24.08
1	1	1	1	-0.23	-23.03	-23.03
1	1	1	1	-0.11	-18.87	-18.87
1	1	1	2	-0.33	-11.51	-11.51
1	1	1	2	-0.46	-16.02	-16.02
1	1	1	2	-0.32	-11.16	-11.16
1	1	1	2	-0.41	-14.28	-14.28
1	1	1	2	-0.51	-17.76	-17.76
1	1	1	3	-0.88	-15.60	-15.60
1	1	1	3	-0.77	-11.78	-11.78
1	1	1	3	-0.80	-12.83	-12.83
1	1	1	3	-0.78	-12.13	-12.13
1	1	1	3	-0.82	-13.52	-13.52
1	1	2	1	0.45	0.58	0.58
1	1	2	1	0.46	0.92	0.92
1	1	2	1	0.38	-1.85	-1.85
1	1	2	1	0.37	-2.20	-2.20
1	1	2	1	0.31	-4.28	-4.28
1	1	2	2	-0.05	-1.78	-1.78
1	1	2	2	0.02	0.65	0.65
1	1	2	2	0.00	-0.05	-0.05
1	1	2	2	-0.09	-3.17	-3.17
1	1	2	2	-0.15	-5.26	-5.26
1	1	2	3	-0.49	-2.06	-2.06
1	1	2	3	-0.50	-2.41	-2.41
1	1	2	3	-0.60	-5.88	-5.88
1	1	2	3	-0.47	-1.37	-1.37
1	1	2	3	-0.60	-5.88	-5.88
1	1	3	1	0.90	16.20	16.20
1	1	3	1	0.94	17.59	17.59
1	1	3	1	0.74	10.65	10.65
1	1	3	1	0.84	14.12	14.12

Subject #	Session #	Head tilt	Target tilt	Reading (volt)	Error (deg)	Modified error (deg)
1	1	3	1	0.70	9.26	9.26
1	1	3	2	0.48	16.62	16.62
1	1	3	2	0.56	19.40	19.40
1	1	3	2	0.44	15.23	15.23
1	1	3	2	0.39	13.49	13.49
1	1	3	2	0.50	17.31	17.31
1	1	3	3	0.25	23.63	23.63
1	1	3	3	-0.02	14.26	14.26
1	1	3	3	0.01	15.30	15.30
1	1	3	3	0.05	16.69	16.69
1	1	3	3	0.09	18.08	18.08
1	2	1	1	-0.06	-17.13	-17.13
1	2	1	1	-0.11	-18.87	-18.87
1	2	1	1	-0.42	-29.63	-29.63
1	2	1	1	-0.20	-21.99	-21.99
1	2	1	1	-0.21	-22.34	-22.34
1	2	1	2	-0.45	-15.67	-15.67
1	2	1	2	-0.50	-17.41	-17.41
1	2	1	2	-0.60	-20.88	-20.88
1	2	1	2	-0.30	-10.47	-10.47
1	2	1	2	-0.67	-23.31	-23.31
1	2	1	3	-0.98	-19.08	-19.08
1	2	1	3	-0.78	-12.13	-12.13
1	2	1	3	-0.72	-10.05	-10.05
1	2	1	3	-0.82	-13.52	-13.52
1	2	1	3	-0.70	-9.35	-9.35
1	2	2	1	0.23	-7.06	-7.06
1	2	2	1	0.25	-6.37	-6.37
1	2	2	1	0.19	-8.45	-8.45
1	2	2	1	0.24	-6.72	-6.72
1	2	2	1	0.28	-5.33	-5.33
1	2	2	2	-0.12	-4.22	-4.22
1	2	2	2	-0.14	-4.91	-4.91
1	2	2	2	-0.24	-8.38	-8.38
1	2	2	2	-0.15	-5.26	-5.26
1	2	2	2	-0.14	-4.91	-4.91
1	2	2	3	-0.63	-6.92	-6.92

Subject #	Session #	Head tilt	Target tilt	Reading (volt)	Error (deg)	Modified error (deg)
1	2	2	3	-0.68	-8.66	-8.66
1	2	2	3	-0.79	-12.48	-12.48
1	2	2	3	-0.55	-4.15	-4.15
1	2	2	3	-0.77	-11.78	-11.78
1	2	3	1	0.81	13.08	13.08
1	2	3	1	0.83	13.77	13.77
1	2	3	1	0.83	13.77	13.77
1	2	3	1	0.75	10.99	10.99
1	2	3	1	0.75	10.99	10.99
1	2	3	2	0.54	18.70	18.70
1	2	3	2	0.61	21.13	21.13
1	2	3	2	0.60	20.78	20.78
1	2	3	2	0.45	15.58	15.58
1	2	3	2	0.40	13.84	13.84
1	2	3	3	0.19	21.55	21.55
1	2	3	3	0.20	21.90	21.90
1	2	3	3	0.18	21.20	21.20
1	2	3	3	0.12	19.12	19.12
1	2	3	3	0.33	26.41	26.41
2	1	1	1	0.00	14.81	-14.81
2	1	1	1	0.03	15.83	-15.83
2	1	1	1	0.16	20.25	-20.25
2	1	1	1	0.11	18.55	-18.55
2	1	1	1	0.30	25.01	-25.01
2	1	1	2	0.62	20.89	-20.89
2	1	1	2	1.00	33.82	-33.82
2	1	1	2	0.80	27.02	-27.02
2	1	1	2	0.69	23.28	-23.28
2	1	1	2	1.04	35.18	-35.18
2	1	1	3	1.41	32.77	-32.77
2	1	1	3	1.32	29.70	-29.70
2	1	1	3	1.36	31.06	-31.06
2	1	1	3	1.25	27.32	-27.32
2	1	1	3	1.26	27.66	-27.66
2	1	2	1	-0.41	0.86	-0.86
2	1	2	1	-0.38	1.88	-1.88
2	1	2	1	-0.30	4.60	-4.60
2	1	2	1	-0.39	1.54	-1.54

Subject #	Session #	Head tilt	Target tilt	Reading (volt)	Error (deg)	Modified error (deg)
2	1	2	1	-0.34	3.24	-3.24
2	1	2	2	0.07	2.19	-2.19
2	1	2	2	0.05	1.51	-1.51
2	1	2	2	-0.01	-0.53	0.53
2	1	2	2	-0.07	-2.57	2.57
2	1	2	2	0.00	-0.19	0.19
2	1	2	3	0.65	6.91	-6.91
2	1	2	3	0.65	6.91	-6.91
2	1	2	3	0.53	2.83	-2.83
2	1	2	3	0.43	-0.57	0.57
2	1	2	3	0.48	1.13	-1.13
2	1	3	1	-1.34	-30.77	30.77
2	1	3	1	-0.97	-18.19	18.19
2	1	3	1	-1.01	-19.55	19.55
2	1	3	1	-1.19	-25.67	25.67
2	1	3	1	-1.02	-19.89	19.89
2	1	3	2	-0.74	-25.36	25.36
2	1	3	2	-0.75	-25.70	25.70
2	1	3	2	-0.65	-22.30	22.30
2	1	3	2	-0.65	-22.30	22.30
2	1	3	2	-0.80	-27.40	27.40
2	1	3	3	0.09	-12.13	12.13
2	1	3	3	-0.18	-21.32	21.32
2	1	3	3	-0.19	-21.66	21.66
2	1	3	3	-0.13	-19.62	19.62
2	1	3	3	-0.04	-16.55	16.55
2	2	1	1	-0.14	10.09	-10.09
2	2	1	1	0.12	19.12	-19.12
2	2	1	1	0.23	22.94	-22.94
2	2	1	1	0.14	19.81	-19.81
2	2	1	1	0.21	22.24	-22.24
2	2	1	2	0.57	19.74	-19.74
2	2	1	2	0.58	20.09	-20.09
2	2	1	2	0.55	19.05	-19.05
2	2	1	2	0.84	29.12	-29.12
2	2	1	2	0.88	30.51	-30.51
2	2	1	3	1.01	20.02	-20.02

Subject #	Session #	Head tilt	Target tilt	Reading (volt)	Error (deg)	Modified error (deg)
2	2	1	3	1.11	23.49	-23.49
2	2	1	3	1.33	31.13	-31.13
2	2	1	3	1.26	28.70	-28.70
2	2	1	3	1.28	29.40	-29.40
2	2	2	1	-0.38	1.76	-1.76
2	2	2	1	-0.36	2.45	-2.45
2	2	2	1	-0.28	5.23	-5.23
2	2	2	1	-0.35	2.80	-2.80
2	2	2	1	-0.36	2.45	-2.45
2	2	2	2	0.03	0.99	-0.99
2	2	2	2	-0.06	-2.13	2.13
2	2	2	2	-0.01	-0.40	0.40
2	2	2	2	0.00	-0.05	0.05
2	2	2	2	-0.02	-0.74	0.74
2	2	2	3	0.27	-5.67	5.67
2	2	2	3	0.38	-1.85	1.85
2	2	2	3	0.29	-4.98	4.98
2	2	2	3	0.44	0.23	-0.23
2	2	2	3	0.40	-1.16	1.16
2	2	3	1	-1.09	-22.90	22.90
2	2	3	1	-0.82	-13.52	13.52
2	2	3	1	-0.69	-9.01	9.01
2	2	3	1	-0.74	-10.74	10.74
2	2	3	1	-0.97	-18.73	18.73
2	2	3	2	-0.56	-19.49	19.49
2	2	3	2	-0.35	-12.20	12.20
2	2	3	2	-0.31	-10.81	10.81
2	2	3	2	-0.32	-11.16	11.16
2	2	3	2	-0.39	-13.59	13.59
2	2	3	3	0.16	-9.49	9.49
2	2	3	3	0.15	-9.84	9.84
2	2	3	3	0.21	-7.76	7.76
2	2	3	3	0.15	-9.84	9.84
2	2	3	3	0.10	-11.58	11.58

A.4 Row data from VKSIM.II experiment

Head Position	Target Position	Reading (volts)	Indication (degree)	Error (degree)
1	1	0.41	14.19	-0.81
1	1	0.25	8.63	-6.37
1	1	0.32	11.06	-3.94
1	1	0.41	14.19	-0.81
1	1	0.33	11.41	-3.59
1	2	-0.1	-3.52	-3.52
1	2	0.05	1.69	1.69
1	2	0.04	1.34	1.34
1	2	0.08	2.73	2.73
1	2	0.03	0.99	0.99
1	3	-0.52	-18.10	-3.10
1	3	-0.43	-14.98	0.02
1	3	-0.62	-21.58	-6.58
1	3	-0.35	-12.20	2.80
1	3	-0.35	-12.20	2.80
2	1	0.37	12.80	-2.20
2	1	0.31	10.72	-4.28
2	1	0.19	6.55	-8.45
2	1	0.26	8.98	-6.02
2	1	0.15	5.16	-9.84
2	2	-0.07	-2.48	-2.48
2	2	0.09	3.08	3.08
2	2	-0.07	-2.48	-2.48
2	2	-0.01	-0.40	-0.40
2	2	-0.03	-1.09	-1.09
2	3	-0.55	-19.15	-4.15
2	3	-0.66	-22.97	-7.97
2	3	-0.53	-18.45	-3.45
2	3	-0.49	-17.06	-2.06
2	3	-0.38	-13.24	1.76
3	1	0.46	15.92	0.92
3	1	0.25	8.63	-6.37
3	1	0.27	9.33	-5.67
3	1	0.37	12.80	-2.20
3	1	0.2	6.90	-8.10

Head Position	Target Position	Reading (volts)	Indication (degree)	Error (degree)
3	2	-0.12	-4.22	-4.22
3	2	-0.1	-3.52	-3.52
3	2	-0.06	-2.13	-2.13
3	2	0.04	1.34	1.34
3	2	0.04	1.34	1.34
3	3	-0.43	-14.98	0.02
3	3	-0.42	-14.63	0.37
3	3	-0.28	-9.77	5.23
3	3	-0.26	-9.08	5.92
3	3	-0.16	-5.60	9.40

A.5 Row data from VKSIM.III experiment

Head Position	Target Position	Reading (volts)	Indication Error(degree)
1	1	-3.54	-14.33
1	1	-3.66	-17.41
1	1	-3.84	-22.03
1	1	-3.76	-19.97
1	1	-3.78	-20.49
1	2	-4.01	-11.38
1	2	-4.06	-12.67
1	2	-4.16	-15.23
1	2	-4.16	-15.23
1	2	-4.37	-20.62
1	3	-4.66	-13.05
1	3	-4.67	-13.31
1	3	-4.64	-12.54
1	3	-4.63	-12.28
1	3	-4.89	-18.95
2	1	-2.93	1.31
2	1	-3.09	-2.79
2	1	-3.29	-7.92
2	1	-3.01	-0.74
2	1	-3.22	-6.13
2	2	-3.66	-2.41
2	2	-3.73	-4.21
2	2	-3.9	-8.56
2	2	-3.75	-4.72
2	2	-3.77	-5.23
2	3	-4.28	-3.31
2	3	-4.35	-5.10
2	3	-4.44	-7.41
2	3	-4.25	-2.54
2	3	-4.31	-4.08
3	1	-2.53	11.56
3	1	-2.61	9.51
3	1	-2.68	7.72
3	1	-2.73	6.44
3	1	-2.83	3.87

Head Position	Target Position	Reading (volts)	Indication Error(degree)
3	2	-3.09	12.21
3	2	-3.28	7.33
3	2	-3.18	9.90
3	2	-3.03	13.74
3	2	-3.21	9.13
3	3	-3.57	14.90
3	3	-3.53	15.92
3	3	-3.67	12.33
3	3	-3.59	14.38
3	3	-3.58	14.64

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